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Research on Sustainable Evaluation Model of Sponge City Based on Emergy Analysis

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Abstract: Sponge city is a method of managing rain floods, proposed by China to deal with urban waterlogging and the overflow pollution of drainage pipe networks, which indicates a more effective strategy to promote urban sustainable development. Due to the diversity of sponge city construction objectives and the complexity of the developmental system, a unified and effective sustainability evaluation method has not yet been formed. Based on the emergy analysis method, the indicators of ecosystem service, the construction cost, the runoff regulation, and the pollutant reduction of sponge city construction are thus included in the evaluation system, and the sustainable evaluation model of a sponge city is fully constructed. Taking the core area in the south of Haicang in Xiamen City as the studying object, the runoff regulation, and the pollutant reduction indicators, are carefully obtained by using Info Works simulation software. The results showed that: ① the quality of COD (Chemical Oxygen Demand) of pollutants discharged from the research object is 409.8t/a, the total runoff is 3.579 million m^3/a, the current annual total runoff control rate is 37.15%, and the current emergy index ESI of sponge city system is $0.05 < 1$, which is in an unsustainable state, It is necessary to upgrade and transform the urban underlying surface; ② The transformation intensity of three LID (Low Impact Development) facilities, i.e., concave green space, permeable pavement and green roof, is carefully selected as different construction schemes. When the construction intensity of LID is 25%, the emergy index ESI (Emergy Sustainable Index) = 1.08, which meets the basic requirements of sustainable development; As long as the reconstruction construction intensity is 30%, the growth value of ESI, ΔESI, is the largest, the sustainable growth effect of sponge city construction is the most obvious, and the marginal benefit is the largest; ③ As long as the total annual runoff control rate of the research object is 69–82%, its sustainable energy index ESI should be within the range of 1.39–1.83. If ESI is less than 1.39, this indicates that the total annual runoff control rate of the research area cannot adapt to the planning requirements of 69%.

Keywords: sponge city; emergy analysis; sustainability evaluation; info works simulation

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1. Introduction

China has experienced the largest and fastest urbanization process in the history of the world and has made remarkable achievements in urban construction and development. However, with the rapid urbanization process, the resource environment of "Less water, more water, and dirty water" and the safety of flood control and drainage in most Chinese cities have directly affected the quality of urban construction and the quality of life of residents. Developed countries such as European countries and the United States, which are also suffered from the urban "water problem", have carried out a lot of research and practice relatively early. Among them, the United States has formed two rain flood management strategies, namely, best management practices (BMPs) and low impact development (LID) [1–3], and the United Kingdom has proposed the construction of sustainable urban drainage system (SUDs) [4]. Its scientific and mature technology provides a reference for urban rain water management in developing countries; Australia proposes water sensitive urban design (WSUD) [5] to provide water sources for landscape irrigation and soil water supplement for the urban environment, so as to maximize the use of existing vegetation and green space to improve the urban microclimate; New Zealand has carried out the low impact urban design and development project [6], which has promoted to achieve a good integration between the ecosystem and the urban drainage system; Singapore proposes ABC (Active, Beautiful and Clean Water) Project [7], as a new sustainable rainwater management method, which seamlessly integrates the environment, water body, and community. Since 2012, the Chinese Central Government has repeatedly stressed that it is necessary to minimize the impact of urban development and construction on the natural ecology, and give priority to the use of natural forces for water storage, drainage, and purification, so that cleaner water can be turned into useful resources, excess water will not result in disasters, polluted water will be purified at all, and thus accelerate the construction of a sponge city with "Natural Accumulation, Natural Penetration, and Natural Purification". In 2015 and 2016, two batches of 30 national sponge city pilot projects were formally approved and funded, and a set of replicable sponge city construction systems, experiences, and practices were explored and formed. In 2021 and 2022, the three ministries and commissions of the state will continue to determine two batches of 30 cities to carry out typical demonstrations through competitive selection, and systematically promote the construction of sponge cities of the whole region.

However, in these relevant practices at home and abroad, due to the lack of unified evaluation standards, the diversity of sponge city objectives, and the complexity of the whole system, there are problems with different evaluation indicators and very difficult to measure in a unified way. There are few studies on the sustainability evaluation model of a sponge city [8], and it is urgent to carry out sustainability evaluation research on sponge city construction. In the 1980s, H.T. Odum, an American ecologist, put forward the emergy theory and analysis method [9], believing that all material energy on the earth comes directly or indirectly from solar energy, and energy with different forms and properties (such as natural resources, economic products, human services, etc.) can be converted into solar energy through solar energy value conversion rate. Emergy theory can solve the problems that different materials and energy in the system have different forms and dimensions and cannot be measured uniformly, and realize the unified measurement of social, economic, and ecological values. Emergy analysis has been widely used in various system assessments, such as Economic Development, Ecosystem [10,11], Agricultural Production [12,13], Pollution Control [14,15], Resource Assessment [16,17], Wastewater Treatment [18,19], and Energy Utilization [20,21]. In assessing the sustainability of the urban system, Qi [22] and others took the water treatment plant as an example and improved the emergy evaluation index system to assess its environmental sustainability according to the characteristics of the water supply system (especially considering the impact of pollutant discharge); Zhang Junxue et al. [23] used emergy theory to quantitatively evaluate the sustainability of environmental governance. These studies apply emergy analysis method to sponge cities with complex ecosystems and solve the problem that it is difficult to measure the environmental and ecological benefits. It can be seen that the emergy analysis method can solve the problem that different substances and energies in the system have different manifestations and cannot be measured uniformly, convert different dimensions into solar energy values, and achieve unified measurement of social, economic, and ecological values. The emergy indexes can quantitatively evaluate the sustainability of a system.

This study uses the emergy analysis method of ecological economics to establish a sponge city sustainability evaluation model, unifies the dimensions of each indicator, comprehensively considers the impact of economic, social, and ecological factors, measures the sponge city construction goal, and uses ESI and other key emergy indicators to evaluate the sustainability of the sponge city construction scheme. This evaluation method makes up for the shortcomings of the original evaluation method focusing on economic or engineering aspects, and provides guiding suggestions for the formulation and optimization of the sponge city planning scheme, so as to provide model verification examples and reference standards for the construction of the sponge city.

2. Materials and Methods

2.1. Research Scope

Xiamen is one of the first batches of sponge city construction pilot cities in China. The core area in Southern Haicang is the key area of Xiamen Sponge City Construction. The land types include residential, administrative, commercial, cultural and sports facilities, municipal facilities, road transportation, Class I industrial land, Class II logistics storage land, park green space, flat land, and water-covering area. The whole research area is 3.20 square kilometers. See Figure 1 for details below.

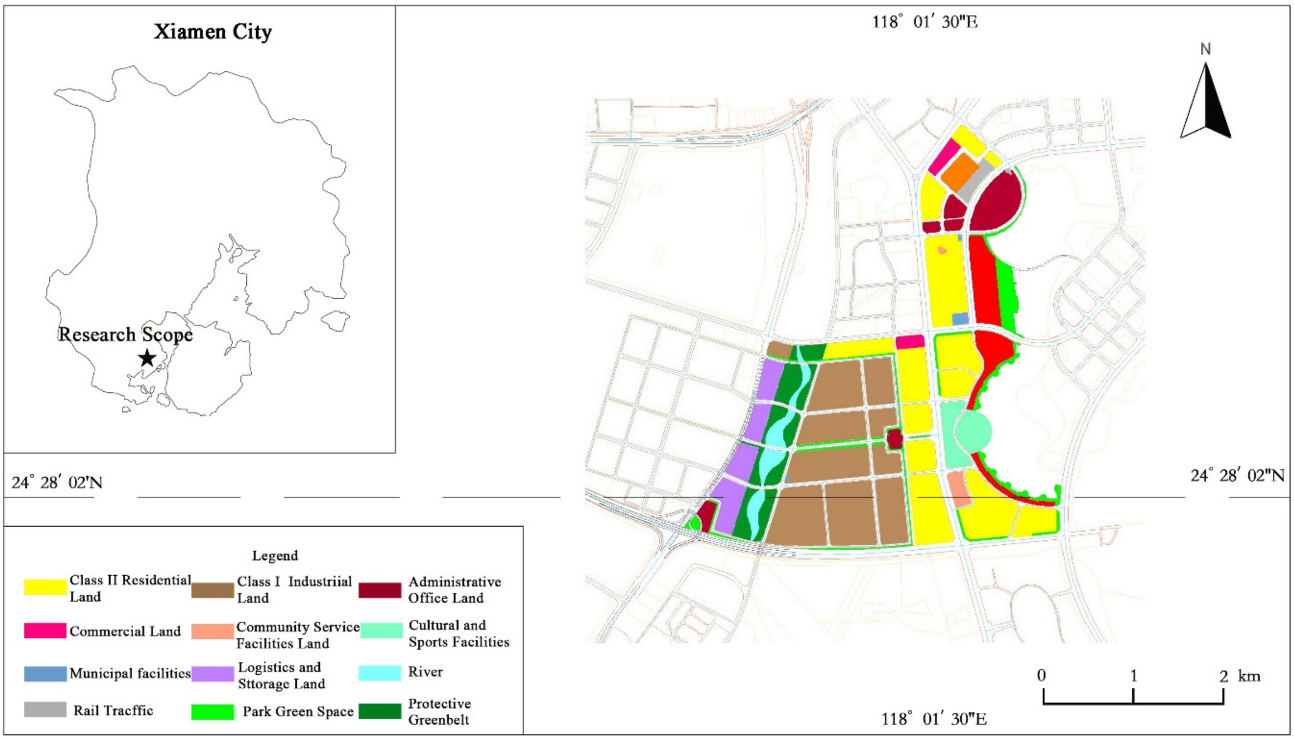

Figure 1. The Location Map of Researching Object.

Based on the imagery 3D map generated by UAV, different types of underlying surfaces are comprehensively interpreted, mainly including roads, green spaces, building roofs, rivers, etc., the area and proportion of each underlying surface are shown in Table 1, and the underlying surface of the study area is shown in Figure 2.

Table 1. The Area and Proportion of the Underlying Surface.

Land Type	Occupation Area (hm^2)	Occupation Ratio (%)
Building Roof	63.55	15.76
Road	50.25	19.93
Urban Green Space	70.65	22.15
Ordinary Hardened Pavement	124.68	39.10
River Course	9.77	3.06

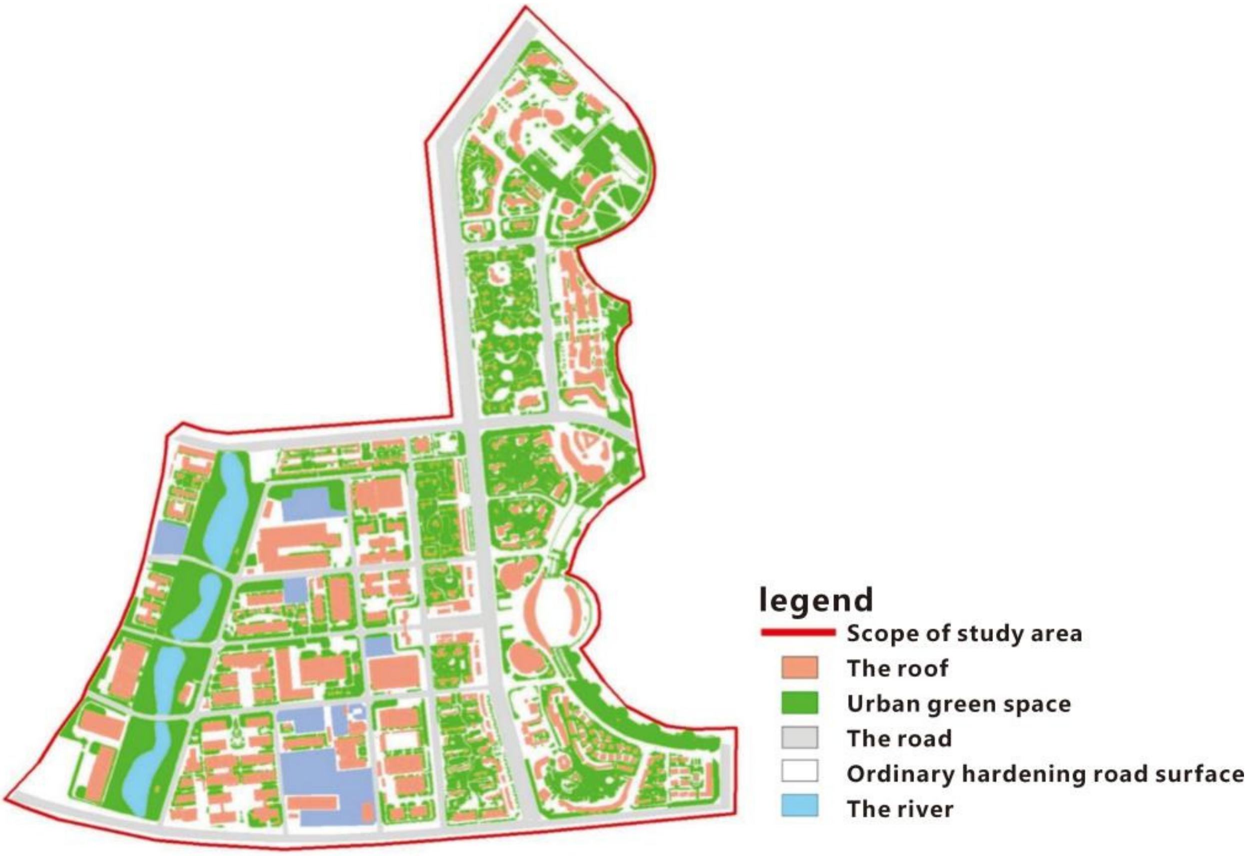

Figure 2. The Analysis of Underlying Surface of Study Area.

2.2. Technical Route

In this study, the emergy analysis method is used to evaluate the sustainability of the sponge city, and an emergy analysis-based evaluation model for the sustainability of the sponge city is constructed. The emergy system diagram is used to sort out the internal structure, emergy input, and output of the sponge city system, and emergy indicators EER, ELR, EYR, and ESI are used to evaluate the sustainability of the system. In addition, the InfoWorks software was used to establish the drainage pipe network model in the study area to obtain runoff regulation and pollutant reduction.

In order to provide optimization strategies for the sponge city construction scheme in the study area, based on the simulation and analysis of the current situation, the reconstruction and construction intensity of three kinds of LID facilities, i.e., concave green space, permeable pavement, and green roof, were specially selected as the optimization object, the eight schemes were evaluated, and the sustainable development indicators are used for better optimization. The research technology route is shown in Figure 3 below.

2.3. Emergy Analysis

2.3.1. The Diagram of Emergy System

Urban water system mainly includes water supply system, drainage system, and rainwater system. Urban water includes residential water and industrial water. In addition, there is water for road sprinkling and vegetation watering. When the water demand cannot be met in the research area, it is necessary to rely on the running water, provided by the external system to maintain the effective urban operation. The local residents of a sponge city can use reclaimed water for irrigation of green land and other water with low water quality requirements by strengthening rainwater utilization and reclaimed water reusing, so as to reduce the total dependence of the system on running water from outside and bring about more internal benefits. Urban rainfall can result in surface runoff, recharge groundwater, or the flowing into the urban ecosystem (urban green space, rain garden, biological retention facilities, etc.) to be absorbed and utilized by all kinds of plants. The construction of LID facilities can increase the number of channels of rainwater in the system, thus improve the efficiency of rainwater infiltration, evaporation, and utilization, so as to generate more ecosystem services, such as rainwater utilization, runoff regulation, pollutant reduction, energy saving, etc. At the same time, the construction and later maintenance of LID facilities also require capital investment from external systems. Therefore, LID facilities are a micro system that requires both economic investment and ecological benefits. The ecosystem provides a series of ecosystem services for sponge cities, such as carbon sequestration and pollutant reduction. These ecosystem services are the environmental benefits that human beings depend on for human survival and can be regarded as the products of nature on earth. In order to make the model more convenient to work, the rain and sewage drainage system in the research area is set up. On the one hand, the rain and sewage drainage system in the research area is completely separated; On the other hand, the sewage treatment rate in the research area is 100%, and the point source pollution is not included, and only the non-point source pollution of rainwater is carefully considered. For the non-point source pollution caused by the urban rainwater runoff, most of the pollutants will enter the drainage pipe network along with the initial rainwater and be discharged to the environment to cause serious pollution. LID facilities can reduce non-point source pollution and purify the rainwater by intercepting and storing the rainwater. Combining the material and energy flow paths of the above sponge city system, the energy system diagram of the water system of the sponge city is drawn, as shown in Figure 4 below.

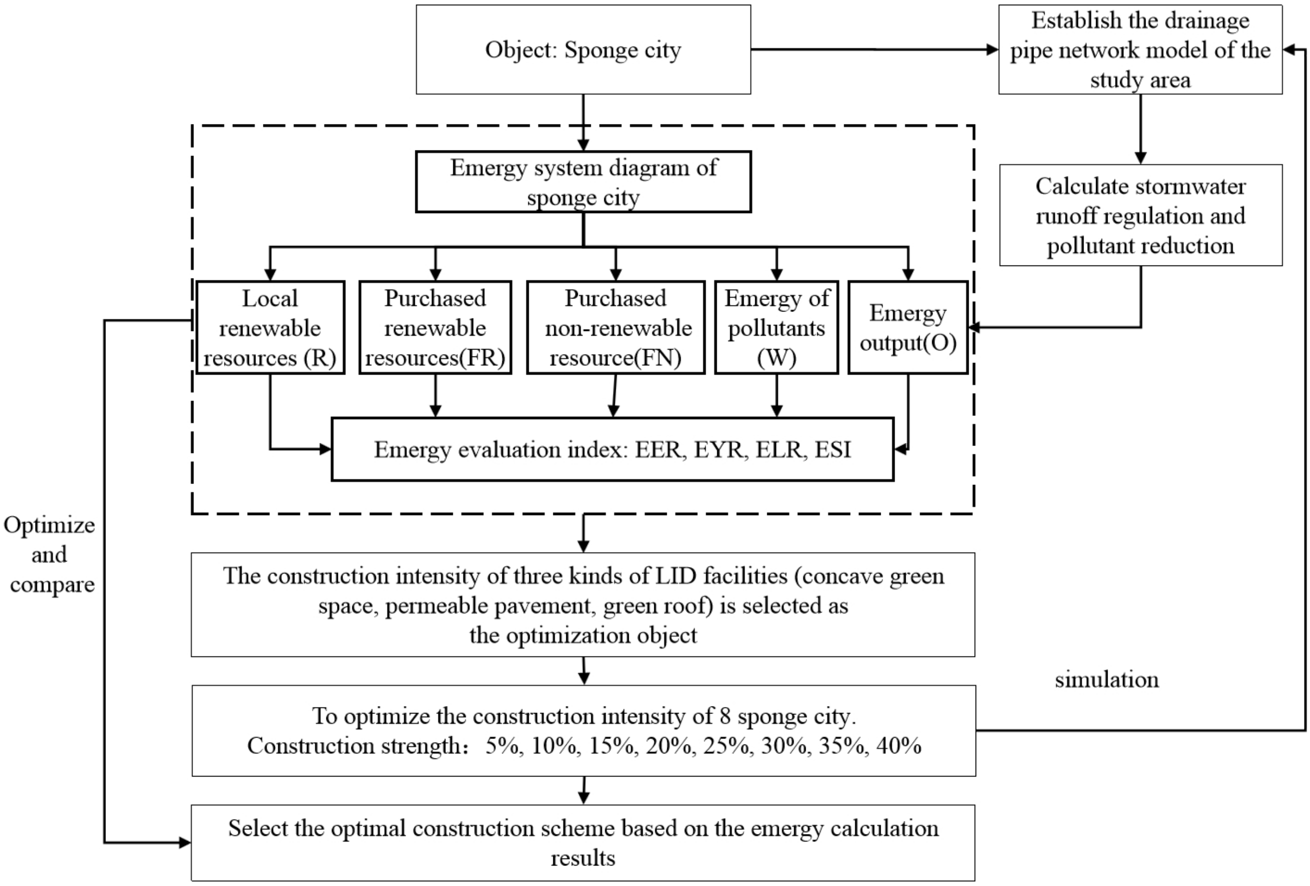

Figure 3. The Technical Roadmap.

2.3.2. Emergy Index

According to different purposes of using, various scholars have proposed different emergy indexes to evaluate the system, and the sustainability of the system can be evaluated using emergy indexes [24–26]. In this paper, four evaluation indexes are mainly selected, including Emergy Exchange Rate (EER), Emergy Output Rate (EYR), Environmental Load Rate (ELR), and Sustainable Development Index ESI. Every formula and meaning of each index are shown in Table 2 below.

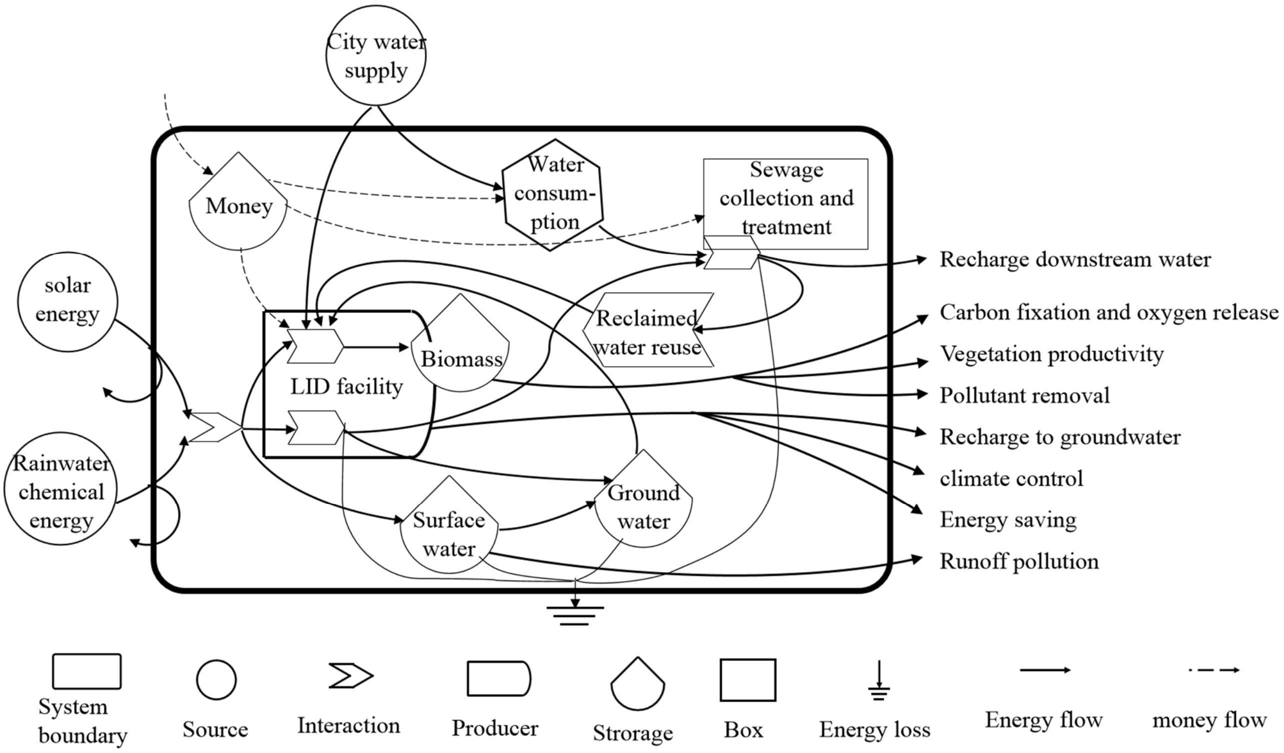

Figure 4. The Emergy System Diagram of Water System in Sponge City.

Table 2. The List of Emergy Index.

Index	Symbol	Meaning
Local renewable resources	R	Local renewable energy value, such as solar energy
Purchased renewable resources	FR	Renewable resources input by external system
Purchased non-renewable resources	FN	Non renewable resources input by external system
Emergy input	$Y = R + FR + FN$	Total energy value used by the system
Emergy of pollutants	W	Pollutants emitted by the system
Emergy output	O	The emergy output of the system
Emergy Exchange Rate	$EER = O/Y$	Emergy output corresponding to unit emergy input
Emergy Yield Rate	$EYR = O/(FR + FN + W)$	The ratio of total emergy output to the sum of socio-economic input emergy and pollutants
Environmental Load Ratio	$ELR = (FN + W)/(R + FR)$	Ratio of the sum of non-renewable emergy inputs and pollutants to renewable emergy inputs
Emergy Sustainable Index	$ESI = EYR/ELR$	Measuring the sustainable development ability of the system. When $1 < ESI < 10$, the system is sustainable

2.4. Data Source and Processing

The data used in this study are from the planning documents of the study area, statistical data on the official website of Xiamen Natural Resources and Planning Bureau, and relevant references.

The construction of a sponge city can produce a series of ecological services to provide ecological and social benefits for the city. The calculation is as follows:

2.4.1. Runoff Regulation and Reduction of Pollutants

Use InfoWorks ICM to establish the hydrological and water quality model of the study area, and obtain the indicators of the total annual runoff and pollutant reduction that are close to the real situation. The steps to establish the icm model are as follows:

1. Division of Sub-Catchment Area

In this paper, the "Thiessen Polygon Rule" is used to sustainably generate the sub-catchment area where each kind of node is accurately located. Thus, improving the attribute setting can be improved, types and proportions of underlying surfaces can be added, and automatically the locating area and quantity of different underlying surfaces through the Info Works ICM software extracted and calculated automatically [27].

2. Generalization of Drainage System

The rainwater pipe network data in the whole research area includes rainwater inlet, well, and pipeline inspection. The data from ArcGIS Model are imported into Info Works ICM software after detailed and smooth data screening and sorting. A total of 578 nodes and 571 pipelines are all imported, as shown in Figure 5 below.

Figure 5. The Schematic Diagram of the Hydrological Model in the Research Area.

3. Rainfall Event Setting

The total precipitation in the research area in 2019 was 1455.3 mm, which was closest to the amount of annual average rainfall of 1427.9 mm. The actual amount of rainfall in 2019 collected by the Xiamen meteorological station was regarded as a typical year for the rainfall event, as is shown in Figure 6 below.

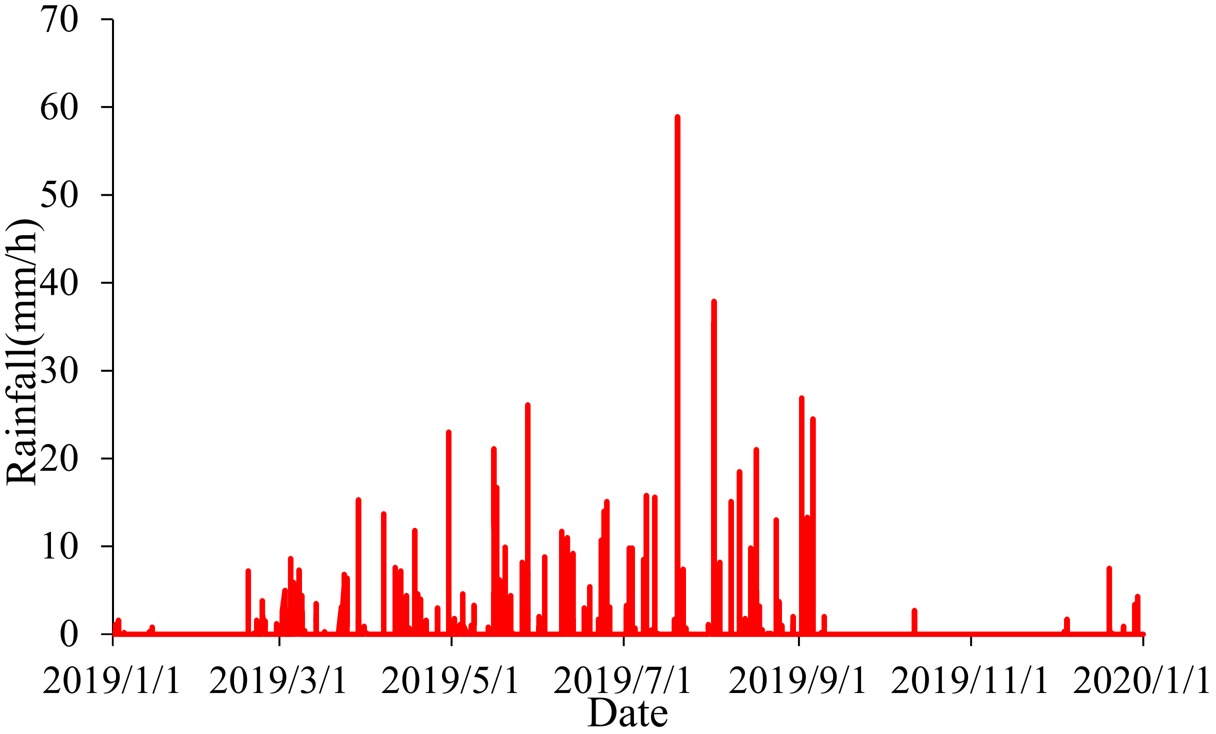

Figure 6. The Hourly Data Information for Actual Rainfall in 2019.

2.4.2. Other Data

1. Net primary productivity (NPP)

Under the effect of photosynthesis, plants can convert solar energy into plant biomass, which is the basic material for human survival. Use CASA (Carnegie Ames Stanford approach) to estimate net primary productivity (NPP), g/m^2:

$$NPP = APAR \times \varepsilon$$

$$APAR = SOL \times FRAR \times 0.5$$

$$FRAR = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}}$$

$APAR$ represents the photosynthetic effective radiation absorbed by all kinds of plants, MJ/m^2; ε is the light energy conversion rate of the plant, taking the maximum light energy utilization rate under the ideal state, 0.542 g/MJ; SOL is the total solar radiation, taking 5.046×10^3 MJ/(m^2 × yr); $FRAR$ is the effective radiation absorption ratio of photosynthesis, $NDVI$ is the normalized vegetation index, which is taken as 0.1801 in Xiamen [28], $NDVI_{\min}$ takes 0.023, $NDVI_{\max}$ takes 0.634 [29]; 0.5 is the effective radiation ratio absorbed and utilized by the vegetation from the total solar radiation.

2. Carbon Fixation and Oxygen Release

Calculation formula for carbon fixation and oxygen release of vegetation:

$$Q_{CO_2} = P_{CO_2} \times NPP \times A$$

$$Q_{O_2} = P_{O_2} \times NPP \times A$$

Q_{CO_2}, Q_{O_2} are the material mass of CO_2, O_2, g; P_{CO_2}, P_{O_2} are the carbon conversion coefficient. According to the photosynthesis equation, plants absorb 1.62 g CO_2 and release 1.19 g O_2 for every 1.0 g dry matter formed, so P_{CO_2} takes 1.62 and P_{O_2} takes 1.19; NPP is the annual net primary productivity, g/m^2; A is the area, m^2.

3. Saving Energy

The green roof can resist the high-temperature invasion for the building in summer, reduce the use frequency of the air conditioner, and thus reduce the power consumption:

$$E_{GR} = \gamma S_{GR} d$$

E_{GR} is the energy savings for green roof thermal insulation in summer, J; γ is the energy consumption saved by the unit green roof in summer, taking 3.24×10^6 J/(m^2 × d); S_{GR} is the green roof area, m^2; d represents the number of summer days, taking 120 days (June–September) [30].

4. Mitigation of the Heat Island Effect

Mitigation of the urban heat island effect is expressed by the evaporation of pervious pavement and transpiration of vegetation:

$$E_h = Eev + Etr = k_1 S_{UG} + k_2 S_G$$

E_h is the total evaporation and transpiration of the region, m^3/yr; Eev is the evaporation capacity of permeable pavement, m^3/yr; k_1 is the annual evaporation generated by permeable pavement per unit area, taken as 0.95 m^3/(m^2 × yr); S_{UG} is the permeable pavement area, m^2; Etr is vegetation transpiration, m^3/yr; k_2 is the annual transpiration generated by the green space per unit area, taking 1.19 m^3/(m^2 × yr) [31]; S_G is the green area, m^2; The density of water vapor is 1.00×10^6 g/m^3.

5. Scientific Value

Sponge cities can generate scientific value:

Scientific Research Value = Number of articles × The number of pages × Emergy Conversion Rate. Search the topic words of "Xiamen City + Sponge City" on www.CNKI.Net (query on 5 December 2021), and a total of 134 papers were searched from 2015 to 2021, each of which is about 6 pages, with an average of 114.86 pages per year [32].

3. Results

3.1. The Current Situation Assessment of Research Area

3.1.1. The Result of InfoWorks Simulation

The statistical results showed that during the simulation period, the total rainfall in the research area reached about 5,244,451 m^3, the total discharge is 3,579,424 m^3, and the calculated annual runoff total control rate is 31.75%. According to the basic requirements of Xiamen Sponge City Special Planning Revision (2017–2035) of the research area, the annual total runoff control rate should be no less than 69%, so the current annual total runoff control rate does not meet the requirements of the planning document in this period.

In this paper, COD pollutants were specially selected as the main pollutants of rainwater runoff pollution for more accurate calculation, and the total COD mass of the discharged pollutants in the research area was 409,848 kg/yr.

3.1.2. Emergy Analysis

The emergy calculation results of the current situation of the research area are shown in Table 3 and Figure 7 below, and the data information is obviously obtained from Xiamen City planning documents, final references, and National Environmental Accounting Database (NEAD, 2015).

Table 3. Emergy Calculation Table of the Current Situation of the Research Area.

	The Initial Value	Unit	Energy Value Conversion Rate (sej/Unit)	Emergy (sej)	UEV Origin
Local renewable resources (R)				1.14×10^{19}	
Solar Energy	2.58×10^{17}	J	1.00	2.58×10^{17}	[33]
Chemical Energy of Rainwater	4.76×10^{14}	J	2.34×10^{4}	1.11×10^{19}	[34]
Purchased renewable resources(FR)				4.09×10^{20}	
Running Water	6.20×10^{14}	J	6.60×10^{5}	4.09×10^{20}	[35]
Purchased non-renewable resources(FN)				5.28×10^{19}	
Running Water Distribution of Electricity-Consuming	1.35×10^{14}	J	2.21×10^{5}	2.99×10^{19}	[36]
Cost of Sewage Treatment	1.72×10^{7}	\$	1.33×10^{12}	2.29×10^{19}	[36]
Total Input of Emergy Value(Y)				4.73×10^{20}	
Total Output of Emergy Value(O)				5.94×10^{19}	
Runoff Regulation	1.39×10^{14}	J	1.85×10^{5}	2.56×10^{19}	[36]
Carbon Sequestration	8.05×10^{9}	g	3.78×10^{7}	3.04×10^{17}	[37]
Oxygen Release	5.91×10^{9}	J	5.11×10^{7}	3.02×10^{17}	[37]
Mitigation of the Heat Island Effect	1.68×10^{13}	g	5.15×10^{5}	8.66×10^{18}	[38]
NPP	4.97×10^{9}	g	5.78×10^{7}	2.87×10^{17}	[39]
Downstream of the Supplying System	4.63×10^{6}	m^3	5.23×10^{12}	2.42×10^{19}	[40]
Pollutant COD(W)	1.20×10^{14}	J	3.80×10^{6}	4.58×10^{20}	[41]

Notes: 1. Solar Energy = Research Area × Solar Radiation Intensity × (1 − reflectance), where the research area = 3.706×10^7 m^2; Solar Radiation Intensity = 5.046×10^9 J/(m^2 × yr); Reflectance = 0.2 [42]. 2. Chemical Energy of Rainwater = Research Area × Annual Rainfall × Density of Rainwater × Gibbs Free Energy, Wherein Annual Rainfall = 1.5301 m/yr; Rainwater Density = 1.00×10^6 g/m^3; Gibbs Free Energy = 4.72 J/g [21]. 3. Power Consumption of Running Water Distribution = Power Consumption of Running Water of Distribution Unit × Energy of Unit Power, where power consumption of running water of Distribution Unit = 0.3 KW × h/m^3 [43]; Energy per unit Electric Quantity = 3.6×10^6 J/(KW × h) [44]. 4. Unit Sewage Treatment Cost 1.2 yan = 0.185\$. \$-CNY Exchange Rate: 6.47 (query on 4 August 2021). 5. Non-point Source Pollutants = mass of COD × unit energy of COD, where unit energy of COD = 1.47×10^7 J/kg. In this paper, COD, the main pollutant, is used to actually calculate the non-point source pollution in the research area, which was caused by the casual flowing of rainfall on the surface of the ground level [24,45].

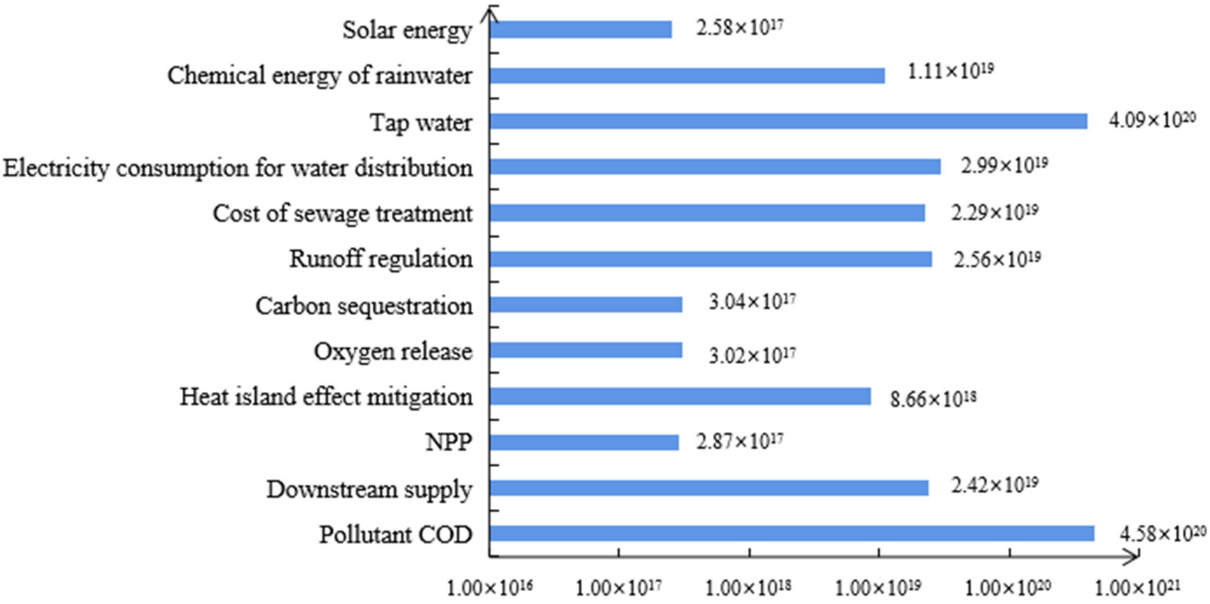

Figure 7. Emergy Input and Output of Sponge City System of the Research Area.

In the current water system in the study area, the emergy value of the input renewable resource FR reaches 4.09 × 10^{20} sej, accounting for 85.84% of all the resources input. This is because there are no available water sources in the study area, including river water, groundwater, sea water, etc., so the study area is highly dependent on external water supply. The water in the area is all tap water delivered from outside the area. The main non-renewable resource input in the system is the distribution power consumption of tap water and the sewage treatment fee, which are 2.99 × 10^{19} sej and 2.29 × 10^{19} sej, respectively. The total energy output O of the system is 5.94 × 10^{19} sej, which is only 12.56% of the total energy Y used in the system, indicating that the system has low resource use efficiency and produces few ecosystem services. Among them, pollutant reduction, water supply downstream, and temperature and humidity regulation are the highest ecosystem services. The pollutant discharged by the system is COD in rainwater, and its total emergy value is 4.58 × 10^{20} sej. The pollutant will have a negative impact on the environment, thus increasing the environmental pressure [45].

The emergy calculation table and the emergy index of the current situation of the research area are shown in Table 4.

Table 4. The Current Emergy Index of the Research Area.

Emergy Index	Number
R	1.14 × 10^{19}
FR	4.09 × 10^{20}
FN	5.28 × 10^{19}
Y	4.73 × 10^{20}
O	5.94 × 10^{19}
W	4.58 × 10^{20}
EER	0.13
ELR	1.22
EYR	0.06
ESI	0.05

As can be seen from the above table, the emergy exchange rate of the current sponge city system in the research area is EER = 0.13 < 1, which indicates that the emergy utilization rate of the system is so low. The environmental load rate ELR = 1.22, mainly because the energy value of untreated stormwater pollutants in the research area is so large that can result in greater environmental pressure. EYR = 0.06, which is because the ecosystem service sector, is generated by the system, while the research area is highly dependent on the external system and relies more on the supply of external input resources. The current emergy index ESI = 0.05 < 1 in the research area indicates that the current system is not in its sustainable phase, (EYR = 0.06) and the large environmental load rate (ELR = 1.22), indicates that the emergy benefit under unit environmental pressure is low, so the system is needed to rapidly increase the total amount of emergy at a high environmental cost, which will easily result in high environmental pressure for nature. The system is not sustainable at all. Therefore, the current sponge city system in the research area is not sustainable, and the sustainability index ESI is very low, so sponge city construction is needed to improve its own sustainable development ability.

3.2. Construction Planning Evaluation

3.2.1. Scheme Setting

The current sponge city system in the practicing area is in a state of unsustainable development. Three common LID facilities that are so easy to implement and maintain, namely permeable pavement, concave green space, and green roof, which are all selected as priority construction measures to smoothly carry out the sponge city reconstruction and the present construction work in the research area.

The comprehensive expansion of the LID construction area will directly change the annual runoff total control rate, the pollutant reduction amount, and other sectors of the ecosystem services of the sponge city. Therefore, the LID construction intensity is specially selected as an independent variable for program optimization. In this paper, the LID facility construction intensity refers to the accurate proportion of the LID facility area to the area that can be transformed immediately. The construction intensity of concave green space is the proportion of concave green space to the total green space area in the study area. In this paper, eight of all the simulation schemes are selected: the LID construction intensity is 5, 10, 15, 20, 25, 30, 35, and 40%. Info Works software simulation is carried out to accurately calculate the emergy index of sponge city, which was under different schemes, and in order to evaluate the sustainability of a sponge city system smoothly.

3.2.2. LID Facility Cost

The LID facility cost is composed of capital construction cost and annual maintenance cost. This paper adopts the life-cycle cost calculation method to estimate current situations. The practicing area is a built-up area with complete urban construction and a complex landscape, so there will be serious problems, such as enormous kinds of social impacts and difficulties in carrying out the facility reconstruction. Under high-density urbanization, the difficulty of LID construction will be worse as long as the construction intensifies, and its cost is in nonlinear direct proportion to the construction intensity [46]. According to the practical experience of sponge construction project already implemented in Xiamen City and combined with expert consultation, this research fits the polynomial of LID unit cost and construction intensity: when the construction intensity is set to 10%, the unit cost will increase by 10%, and when the construction intensity is set to 50%, the unit cost will multiply by twice. According to the above methods, the life-cycle costs of three kinds of LID facilities, under different construction intensities are obviously obtained, as shown in Table 5.

Table 5. Full Life-Cycle Cost of LID (Low Impact Development) Facilities under different construction Level Calculating. Unit: Yuan/Square Meter.

LID Facilities	5%	10%	15%	20%	25%	30%	35%	40%
Concave Greenbelt	309.38	330	361.88	405	459.38	525	601.88	690
Permeable Pavement	391.88	418	458.38	513	581.88	665	762.38	874
Vegetated Roof	464.06	495	329.25	348	386.25	444	521.25	1035

3.2.3. Result Analysis

An amount of eight schemes were smoothly simulated and calculated, and the emergy index is shown in Figure 8. When the construction intensity of LID is 25%, ESI = 1.08, at this time, the sponge city construction in the research area has met the basic requirements of sustainable development. With the gradual increase of LID construction intensity, ESI keeps increasing all the time, which means that the sustainable development ability of the system keeps increasing with the increase of LID construction intensity. However, the growth rate of ESI is not linear. Its growth value ΔESI increases first and then decreases, the sustainable growth rate of the system increases first and then decreases as long as the same construction intensity is increased. When the construction intensity is 30%, the ESI growth value ΔESI is the largest, indicating that the project construction promotes the best sustainable growth effect to the system. Therefore, if the increased value of sustainable development indicator ESI and ΔESI is considered to be the maximum number, 30% can be selected as the optimal one among the eight LID construction schemes in the researching area of all the construction intensity.

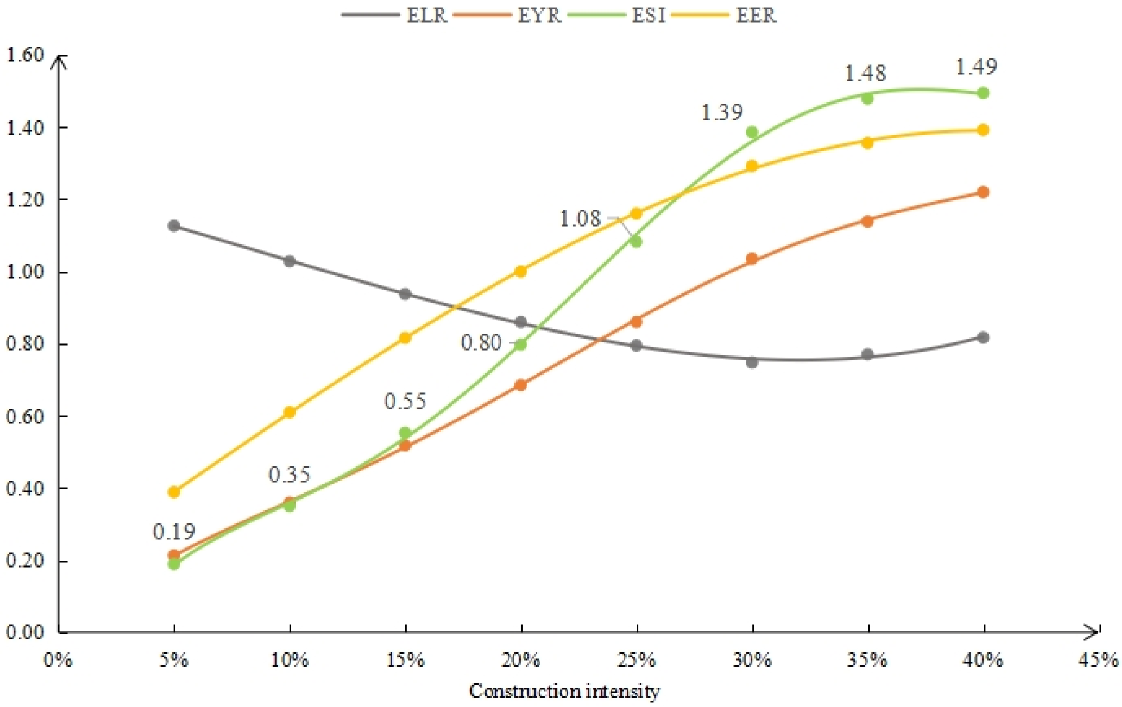

Figure 8. The Emergy Indexes of different Sponge City Reconstruction and Construction Schemes in the Practicing Area.

4. Discussion

Through the detailed information data of comparative analysis, this paper chooses the 30% reconstruction construction intensity scheme as the optimal construction scheme in the practicing area of the sponge city, systematically analyzes the improvement and sustainability of the sponge city system under the optimal scheme, and compares it with the current situation in the whole practicing area.

4.1. Improvement of Drainage Effect

The total runoff of the optimal construction scheme is 1,622,113 m^3, the total annual runoff control rate is 69.07%, the total mass of effluent pollutant COD is 137,862 kg, which is 271,986 kg less than the current situation, and the pollutant reduction rate reaches above 66.36%. After the construction of the practicing area on the basis of the optimal scheme, the drainage situation in the researching area can be greatly changed, the overflow of nodes and the load of pipelines can be alleviated, the discharge and pollutants can be effectively reduced, and the total benefits of runoff regulation and the amount of pollutant reduction can be increased.

4.2. Analysis of the Optimal Scheme of Emergy

4.2.1. Emergy Input and Output

The energy input and output of the current situation of the practicing area and the optimal scheme are compared and analyzed, as shown in Figure 9. In the optimal scheme, the total amount of energy purchased by the whole system is 5.64 × 10^{20} sej, where the input energy value of renewable resources is 4.06 × 10^{20} sej, and the energy value of non-renewable resources is 1.58 × 10^{20} sej. The optimal scheme presupposes the reuse of reclaimed water in the region, but the outside running water is still the biggest, which shows that only 2% of the reclaimed water reuse rate planned in the study area has little effect on reducing the high dependence of regional water use on the outside world. On the one hand, the reuse rate of reclaimed water is low, which plays a small role; on the other hand, the value of reclaimed water is not as high as that of tap water, which can only be used in places with low water quality requirements, such as road sprinkling, greenbelt irrigation, etc. However, the best use of reclaimed water still alleviates the water shortage to a certain extent. Subsequent research can be tried to effectively improve the recycled water recycling rate and deeply study the impact of reclaimed water utilization rate on the sustainability of the system.

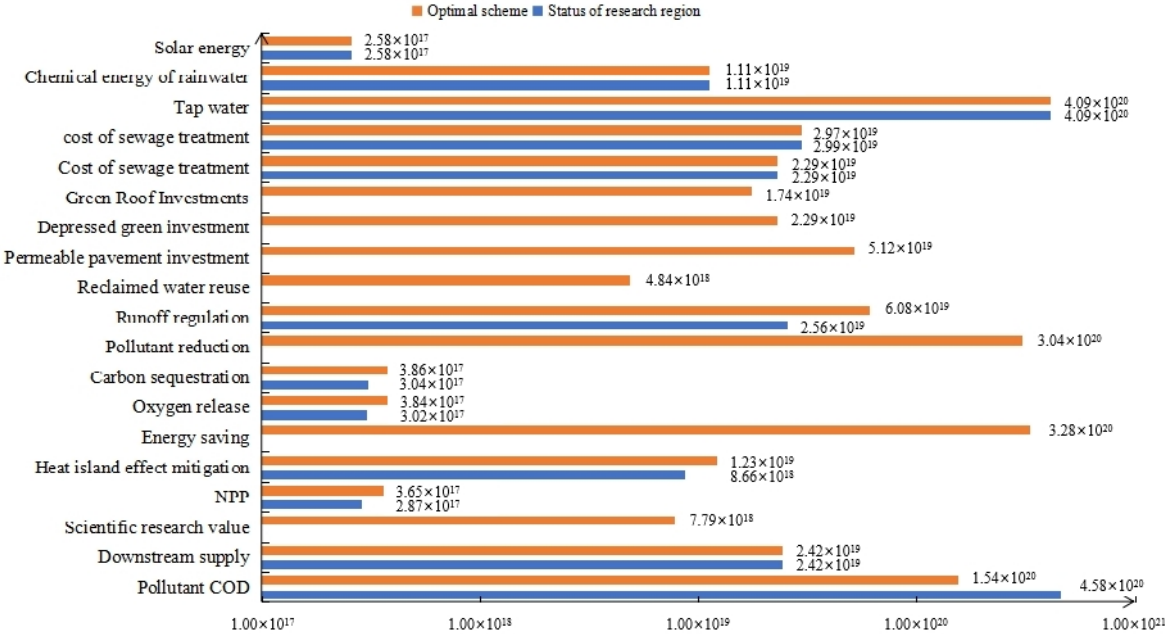

Figure 9. Comparison of Emergy Input and Output of the Current Situation and the Optimal Scheme in the practicing area.

The main non-renewable energy input of the optimal scheme is the input of various LID facilities. The input energy values of green roof, concave green space, and permeable pavement are 3.09×10^{19} sej, 2.29×10^{19} sej, and 5.12×10^{19} sej, respectively, which includes the construction cost and the maintenance cost of the whole life cycle.

The total emergy output of the optimal scheme O (7.43×10^{20} sej) is 12.5 times than that of the current situation of the practicing area (5.94×10^{19} sej), which greatly improves the ecosystem service output of the system, especially the actual benefits brought by pollutant reduction and energy saving by vegetarian roof. The highest ecosystem service is energy-saving service. The emergy value is 3.28×10^{20} sej, which is the benefit brought by the construction of a vegetarian roof. The emergy output O of the optimal scheme increases significantly and exceeds the total emergy Y (5.75×10^{20} sej), indicating that the sponge city system operates emergy more efficiently.

Compared with the current situation of the practicing area, the construction of a sponge city can greatly reduce the emergy value of all kinds of pollutants. In the optimal scheme, the emergy value of COD decreases from 4.58×10^{20} sej to 1.54×10^{20} sej, which greatly reduces the environmental pressure and has a great impact on the sustainability of the urban water system.

4.2.2. Analysis of Emergy Index

The emergy index was obviously calculated and compared with the emergy index results of the current situation in the practicing area, as shown in Table 6.

EER is the ratio of emergy output (O) to emergy input (Y), which represents the efficiency of emergy exchange between the system and the outside world. The larger EER is, the more efficient the system is in converting the input emergy into output emergy. The emergy exchange rate (EER) of sponge city is 1.29, which is higher than that of the current system (0.13), indicating that the emergy utilization efficiency is improving at all, and the emergy output of sponge city is greater than the total emergy input. The sustainability index of sponge city ESI = 1.39 > 1 indicates that the sponge city system under the optimal scheme is so sustainable that the ESI of the optimised system is much larger than that of the current system (0.05). This is because the sponge system can obtain a higher emergy yield rate (EYR = 1.03) by improving all kinds of ecosystem services, and the environmental load rate (ELR = 0.75) is reduced by the LID facility's effect on the total reduction of rainwater pollutants. Thus, the emergy benefit of the system under unit environmental pressure is effectively increased, and the whole system can eventually reach a state of sustainable development.

Table 6. Emergy Index of the Optimal Scheme and the current situation of the practicing area.

Emergy Indices	Current Situation of Practicing Area	The Optimal Solution
R	1.14×10^{19}	1.04×10^{19}
FR	4.09×10^{20}	4.06×10^{20}
FN	5.28×10^{19}	1.58×10^{20}
Y	4.73×10^{20}	5.75×10^{20}
O	5.94×10^{19}	7.43×10^{20}
W	4.58×10^{20}	1.54×10^{20}
EER	0.13	1.29
ELR	1.22	0.75
EYR	0.06	1.03
ESI	0.05	1.39

5. Conclusions and Prospect

The construction of a sustainable sponge city conforms to the development concept of the new era. Therefore, it is of great significance to study the evaluation method of sustainability of sponge city. In this paper, the sustainability evaluation model of sponge cities based on emergy analysis method is constructed, which is transferable and can be applied to the practice of other sponge cities, providing reference standards and calculation templates for the subsequent sustainability evaluation of sponge cities. In addition, the optimization method from the perspective of sustainability can be extended and applied to the construction planning of sponge cities, and provide optimization strategies for the selection of sponge city construction schemes in the future.

Future research could be further from the following two aspects: (1) This article is located in the core area in Southern Haicang, Xiamen for the case study, for a typical coastal land, most of the area belongs to the sea land mass deposition, the future of case selection should have more different scenarios, different geological conditions, further verify the validity of the model, expand the research conclusion of extensionality. (2) This article's research is still in its infancy stage, and failed to intelligent technologies such as the application of intelligent algorithms, the artificial neural network, further research into intelligent algorithms in the sponge scheme optimization of research, and application of the city so as to enrich model scheme Settings, such as adopting different proportions of LID facilities, are studied under different design schemes of sustainability.

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