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Environmental Sustainability Study of Urban Waterfront Landscapes Based on the LCA–Emergy–Carbon Footprint and Artificial Neural Network Method

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Abstract: The ecological landscape design of urban rivers plays a crucial role in mitigating the urban heat island effect and preserving urban ecology. This study focuses on the construction process data of key landscape nodes along Nanjing's urban rivers. By employing a whole life cycle emergy approach and carbon emission method, the sustainable changes in the landscape system are quantitatively assessed. Furthermore, artificial neural networks have been used to conduct long-term sustainability analysis and predictions for the landscape system. The research findings reveal that over time, the maintenance investment in landscape projects gradually becomes dominant, increasing from 2% in the first year to approximately 75% after 30 years. This phenomenon signifies a decline in the efficiency of the landscape system. Sustaining the ecological balance of the landscape system necessitates continuous inputs of material flow, energy flow, and information flow. The major contributors to carbon emissions in the landscape engineering system are diesel fuel, cement, and steel. This highlights opportunities for sustainable improvement from a low-carbon perspective. To enhance the ecological sustainability of urban waterfront landscapes, three measures are proposed: sponge city construction concepts, coupled sewage treatment systems, and information flow monitoring systems. The effectiveness of these measures was preliminarily validated.

Keywords: sustainability; LCA–Emergy–Carbon footprint analysis; artificial neural network method; water landscape system

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1. Introduction

In the face of the deteriorating global environment, an ecologically sustainable urban environment is crucial. The urban system involves numerous environmental impact factors, and rivers possess exceptional characteristics. Through waterfront landscape design, rivers can effectively mitigate the urban heat island effect and reduce carbon emissions in cities [1,2]. The purpose of this study is to provide a feasible approach for urban sustainable development through the ecological and low-carbon assessment and analysis of waterfront landscapes.

Urban waterfront landscapes can protect and restore local ecosystems. Wetlands and vegetation in these landscapes have the ability to filter water, absorb pollutants, and provide habitats for various flora and fauna. The vegetation in waterfront landscapes can absorb harmful gases from the air and release oxygen, thus improving the air quality of cities. Trees and plants also help reduce air temperature and mitigate the urban heat island effect. Urban waterfront landscapes can manage water resources through rainwater collection and treatment systems. These systems can collect and utilize rainwater, reducing the burden on city drainage systems and minimizing the demand for groundwater. Additionally, waterfront landscapes provide recreational activities and social spaces for residents. Contact with natural environments and engagement in outdoor activities are crucial for physical and mental well-being. Moreover, green waterfront landscapes alleviate psychological stress and enhance residents' quality of life. In conclusion, urban waterfront landscapes effectively enhance the ecological standards of cities through their roles in ecosystem protection, air quality improvement, water resource management, and the promotion of community health and well-being [3,4].

The ecological emergy theory is a promising method for conducting sustainable assessment research on urban waterfront landscapes. The theory of emergy, originally introduced in the field of ecology [5–7], has been extended to multiple domains including urban studies [8,9], industrial sectors [10,11], building systems [12,13], and economic fields [14]. Currently, many scholars have coupled the emergy theory with other methods, such as GIS approaches [15,16], carbon emission methods [17,18], ecological footprint methods [19–21], and life cycle assessment (LCA) evaluation [22].

Among them, the LCA–Emergy methodology creates a comprehensive approach that enables the calculation of emergy values throughout the entire lifecycle. This integration ensures the completeness of the assessment. It considers the entire lifecycle of a specific system, including stages such as resource acquisition, manufacturing, use, disposal, and waste management, when assessing its sustainability. By using emergy as a universal unit, this method calculates the emergy consumed and generated by the system at different stages. The key advantage of the LCA–Emergy method is its ability to quantify and comprehensively consider the energy consumption, material flows, and environmental impacts of the system, thereby providing more comprehensive and holistic assessment results. By integrating life cycle theory with the concept of emergy, it enables a better understanding and evaluation of the energy efficiency and environmental performance of the system at different stages, facilitating informed decision-making for sustainability [23–25]. The research on the integration of the LCA–Emergy method with the ecological sustainability of urban waterfront landscapes involves several aspects [26–28], such as: (1) Sustainability assessment: The LCA–Emergy method can serve as one of the tools to assess the ecological sustainability of urban waterfront landscapes. (2) Optimization of waterfront landscapes: By employing the LCA–Emergy method, the performance of different design options can be evaluated and compared in terms of energy, material, and ecological benefits, thereby providing decision support and design recommendations to achieve more sustainable waterfront landscapes. (3) Energy management: By analyzing the flow of emergy and energy conversion processes, critical areas of energy utilization can be identified and optimized to reduce energy waste and promote energy efficiency improvement in waterfront landscapes. (4) Evaluation of ecosystem services: The LCA–Emergy method can be used to assess the value of ecosystem services provided by urban waterfront landscapes. In summary, the LCA–Emergy method can support the design, assessment, and management of urban waterfront landscapes, facilitating the achievement of their ecological sustainability. At the same time, the ecological sustainability of waterfront landscapes can be quantified and analyzed through the application of the LCA–Emergy method, providing a scientific basis for decision-making.

In addition, the integration of LCA and carbon emissions is a recognized methodology for studying the sustainability of systems. The cross-methodology of LCA and carbon emissions is known as carbon footprint assessment, which combines LCA methods with carbon emission calculations to evaluate the carbon emissions generated by products, services, or systems throughout their entire life cycle. By combining LCA with carbon emission calculations, carbon footprint assessment comprehensively considers the carbon emissions associated with products, services, or systems, helping to identify and optimize high-carbon-emitting stages to achieve carbon reduction and sustainable development goals. It can not only be applied in corporate environmental management and product design, but also provides clear carbon information to consumers, promoting sustainable purchasing and consumption behavior [29–37].

Neural network models have potential applications in predicting the sustainable effects of waterfront landscape design to achieve intelligent waterfront landscape design [38–40]. The key steps include: (1) Data collection and feature selection: Collecting relevant data related to the sustainability of waterfront landscapes and performing feature selection for the prediction target. These data may include parameters of waterfront landscape design, environmental indicators, ecosystem service values, etc. (2) Model training and optimization: Utilizing the collected data to train and optimize the neural network model. This involves selecting an appropriate neural network structure, setting model hyperparameters, and training the model using the data to accurately predict the sustainability effects of waterfront landscape designs. (3) Prediction and evaluation: After model training, using the model to predict new waterfront landscape design scenarios. By inputting the corresponding design parameters and features, the model can output predictions such as ecosystem service values, energy utilization efficiency, etc. These predictions can help evaluate the sustainability effects of different design scenarios and support decision-making. (4) Model validation and improvement: To validate the accuracy and robustness of the model, independent test datasets can be used for model validation. If the model performs poorly, improvements can be made by adjusting the neural network structure or parameters, or introducing other enhancement methods.

To date, no scholars have explored the coupling of LCA–Emergy–Carbon with a neural network model to predict the ecological sustainability of waterfront landscapes. This study addresses this research gap and introduces an innovative approach by integrating the LCA, emergy analysis, carbon footprint method, and neural network model to comprehensively analyze the ecological sustainability of waterfront landscapes. This integrated analysis provides a more comprehensive and accurate assessment, revealing the long-term impacts of waterfront landscape design on ecosystems.

Traditionally, assessments of waterfront landscapes have primarily focused on the environmental benefits during the design phase, often overlooking the energy consumption and environmental impacts throughout the entire life cycle. By applying the LCA–Emergy–Carbon approach, this study considers the integrated effects of energy consumption and environmental loadings across various stages, including material acquisition, construction, operation, and decommissioning. The carbon footprint method serves as a measure of human activities' contribution to greenhouse gas emissions. By incorporating the carbon footprint analysis, this study quantitatively evaluates the carbon emissions associated with different waterfront landscape design scenarios, providing guidance for reducing carbon footprints. Additionally, the use of a neural network model enables predictions based on historical data and relevant features, allowing for inference on the impact of waterfront landscape design scenarios on ecological sustainability. This model can handle complex non-linear relationships and provide accurate prediction results.

By combining these three approaches, this study offers a more comprehensive, accurate, and innovative analysis in assessing the ecological sustainability of waterfront landscapes, thereby providing robust support for future waterfront landscape design and decision-making.

2. Materials and Methods

2.1. Research Framework

The study in this paper is based on the methodology of systems engineering to conduct a sustainable assessment of landscape systems. The application of systems engineering methodology and the study of ecological emergy and low-carbon cross-coupling in architecture can help categorize the various input factors of the building system, establish a modular framework, and define structural boundaries. This facilitates comprehensive evaluation and design for the entire building system. In order to establish a research model for the building system, the input types are divided into three categories: material flow, energy flow, and information flow. Figure 1 illustrates the research framework of the entire paper.

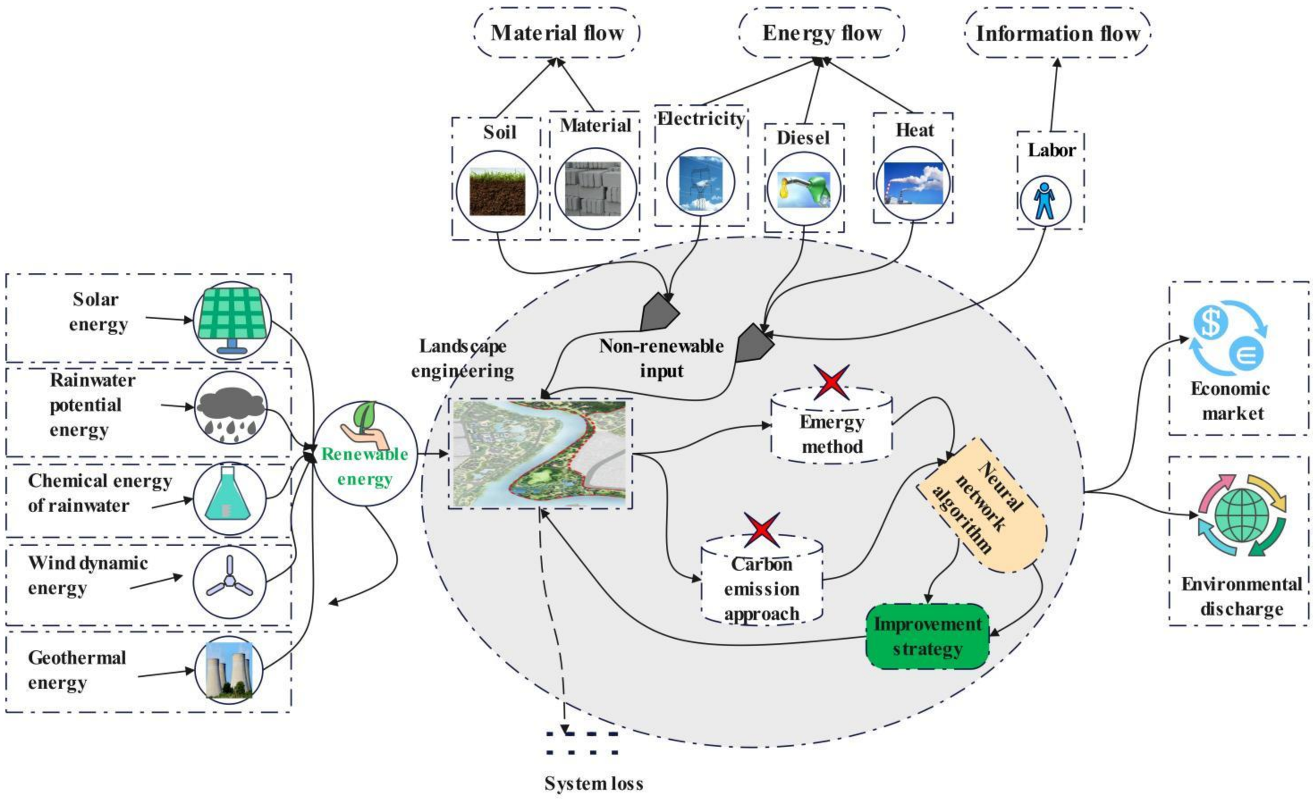

Figure 1. Research framework.

In addition, this paper takes a dynamic approach to the architectural system, involving not only static analysis but also the sustainable aspects and predictions of carbon emissions related to subsequent riverfront landscape projects. This contributes to the enhancement of efficiency for urban managers.

2.1.1. Hypothesis for Research

This article verifies the following three hypotheses through an ecological assessment of urban river landscapes:

(1) Ecological assessments of landscape transformation projects should consider the impact of information lag on sustainability outcomes. In general, information lag can have a negative effect on the overall sustainability performance of the building system, particularly concerning feedback from landscape designers.
(2) The influence of feedback structures should be evaluated to examine their impact on the entire building system. Feedback structures can be categorized into open-loop, closed-loop, and cross-feedback structures.
(3) The effect of water quality in rivers on the ecological sustainability of the entire river landscape, including emergy and carbon emission aspects.

2.1.2. Typical Feedback Structure

The feedback systems are evaluated based on two aspects: ecological energy value and carbon emissions. The three types of feedback systems are open-loop feedback system, closed-loop feedback system, and cross-feedback system. These systems are represented by measures such as energy value quantity, energy value indicators, and carbon emissions. A diagram of the feedback system pathways can be found in Figure 2 of this article.

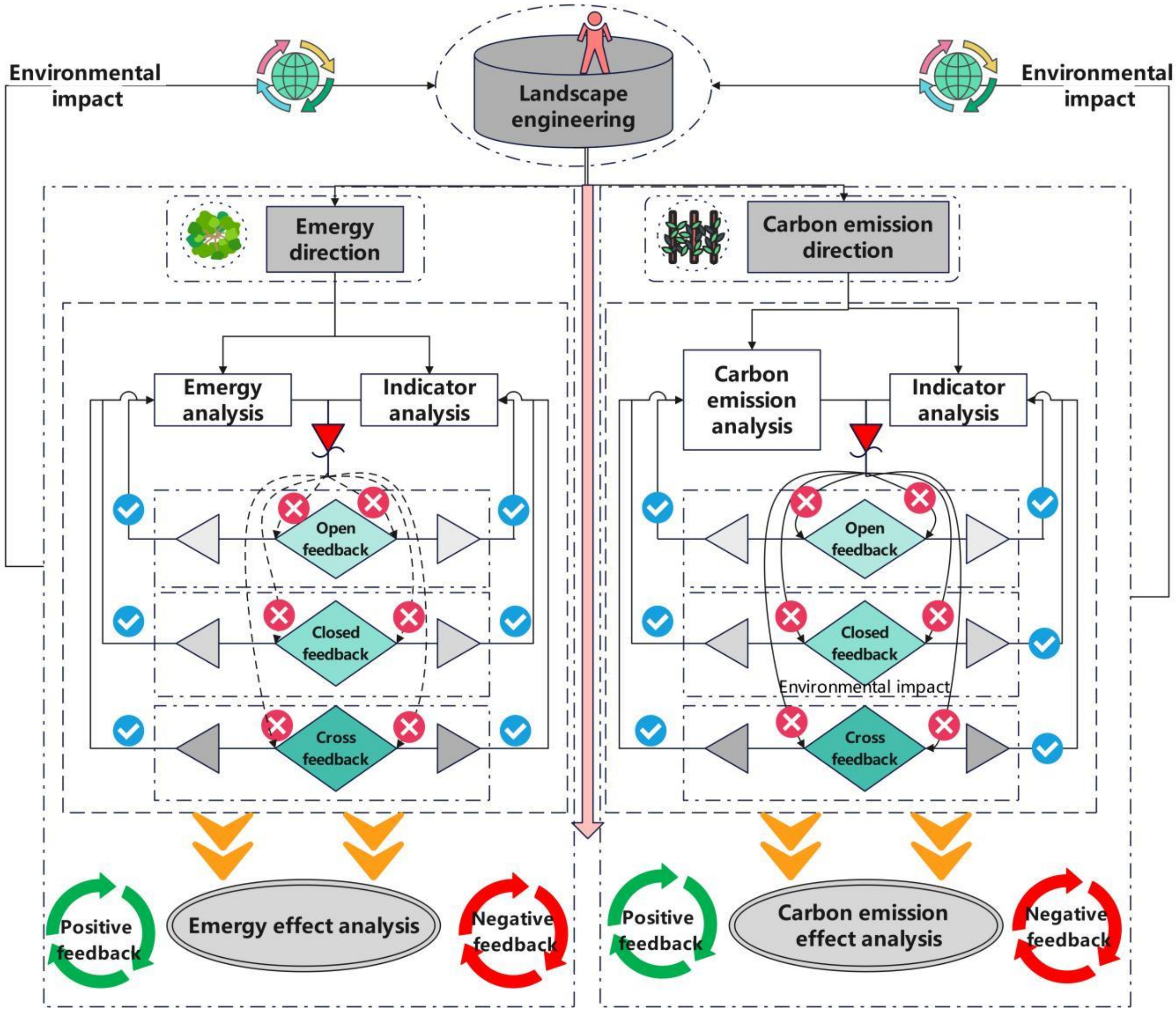

Figure 2. Typical feedback system path.

2.2. LCA–Emergy Model

2.2.1. Emergy Introduction

The ecological emergy method is an analytical approach used to assess and compare the impacts of different decision options on ecosystems. It is based on ecological principles and aims to quantify the value of ecosystems as energy values, helping decision-makers make sustainable choices between environmental conservation and economic development. The ecological emergy method takes into account the structure, functions, and services provided by ecosystems, as well as their contributions to human well-being. By converting these ecological values into emergy values, it becomes possible to compare the costs and benefits of different decision options for ecosystems and reveal their potential environmental benefits and risks. In the ecological emergy method, the first step involves assessing the ecosystem, including data collection and analysis of aspects such as species diversity, ecological processes, and natural resources. Then, by using appropriate indicators and models, the emergy of the ecosystem is quantified as emergy values and integrated into the decision analysis framework. One of the advantages of the ecological emergy method is its ability to quantify the value of ecosystems, allowing for comparisons with economic benefits. This helps raise awareness and appreciation for ecosystems, promoting decision-making that supports sustainable development. Additionally, the ecological emergy method can uncover the ecological risks and uncertainties associated with decision options, aiding decision-makers in better managing environmental issues. The UEVs consist of three types, which are sej/kg, sej/j, sej/USA$, respectively [41].

2.2.2. Emergy Indicators

The sustainability hierarchy can be realized based on a set of emergy indicators [42,43]. In this study, three are four critical indexes that have been displayed in Figure 3.

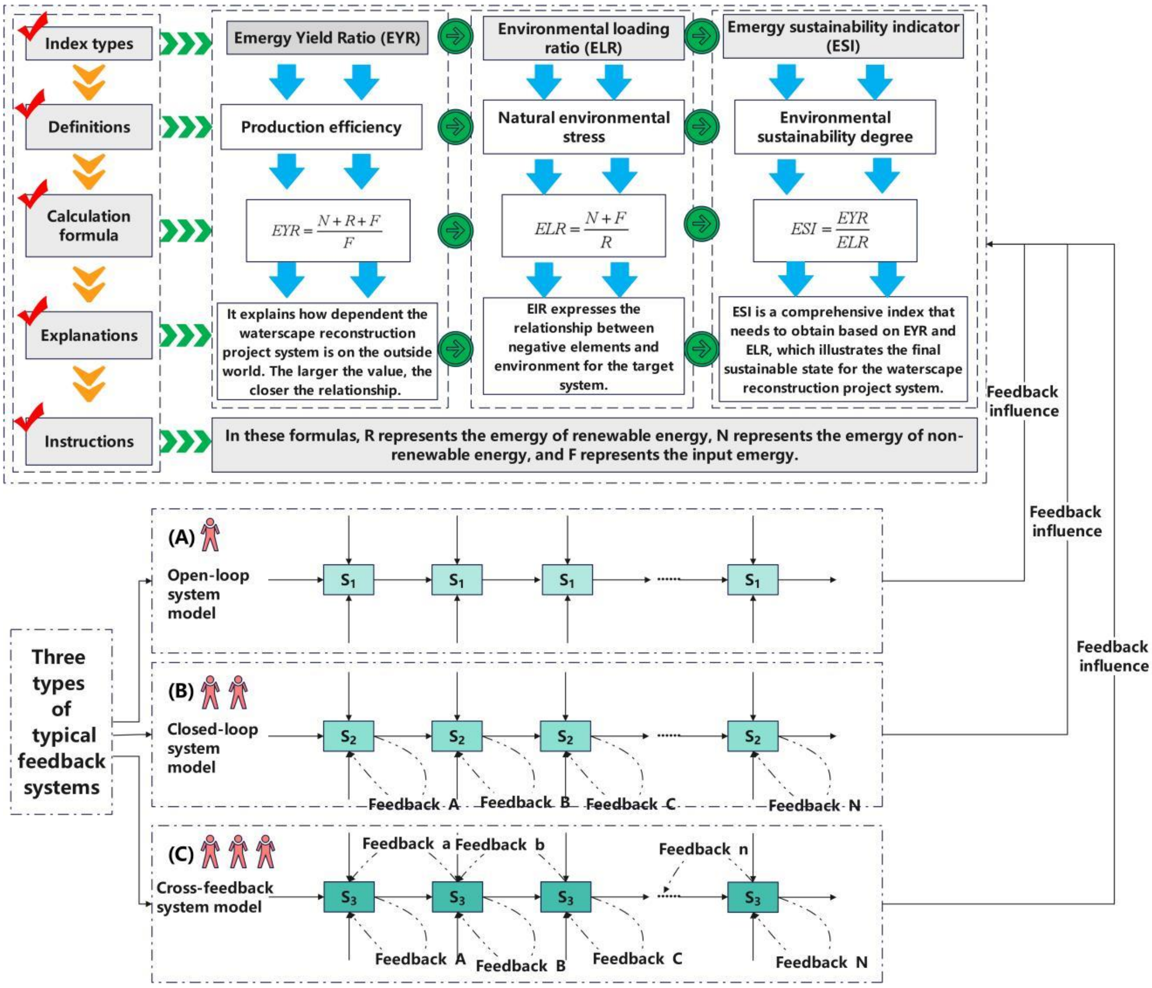

Figure 3. Sustainable index frame diagram of the coupled feedback system.

The environmental loading rate of a landscape system is an indicator that assesses the pressure exerted by the system on environmental resources in terms of resource consumption, energy utilization, waste generation, and pollution emissions. It helps in understanding the extent of the landscape system's impact on the environment.

The emergy yield rate measures the efficiency and output levels of a landscape system in providing ecological services, maintaining ecological functions, and supporting human well-being. It quantifies the system's contribution to energy flow, material cycling, and ecological processes, and evaluates the value it creates for the socio-economic system.

The environmental sustainability indicator comprises a set of indicators and factors used to assess the sustainability performance of a landscape system. These parameters consider factors such as resource use efficiency, ecological conservation capacity, carbon footprint, water footprint, and biodiversity protection, aiming to ensure the harmonious development of the landscape system with environmental protection and achieve long-term sustainable development goals.

These three categories of indicator collectively provide a comprehensive assessment of the landscape system. They consider its impact on the environment (ELR), evaluate its contribution to the socio-economic system (EYR), and also focus on its sustainability performance (ESI). This aids in guiding landscape planning and management, promoting a balance between ecological conservation and economic development.

2.3. LCA–Carbon Calculation Model

In accordance with the national carbon emission calculation standards [44], Figure 4 and Table 1 have been designed and presented. Figure 4 represents the carbon emission implementation pathway, while Table 1 depicts the carbon sink calculation pathway.

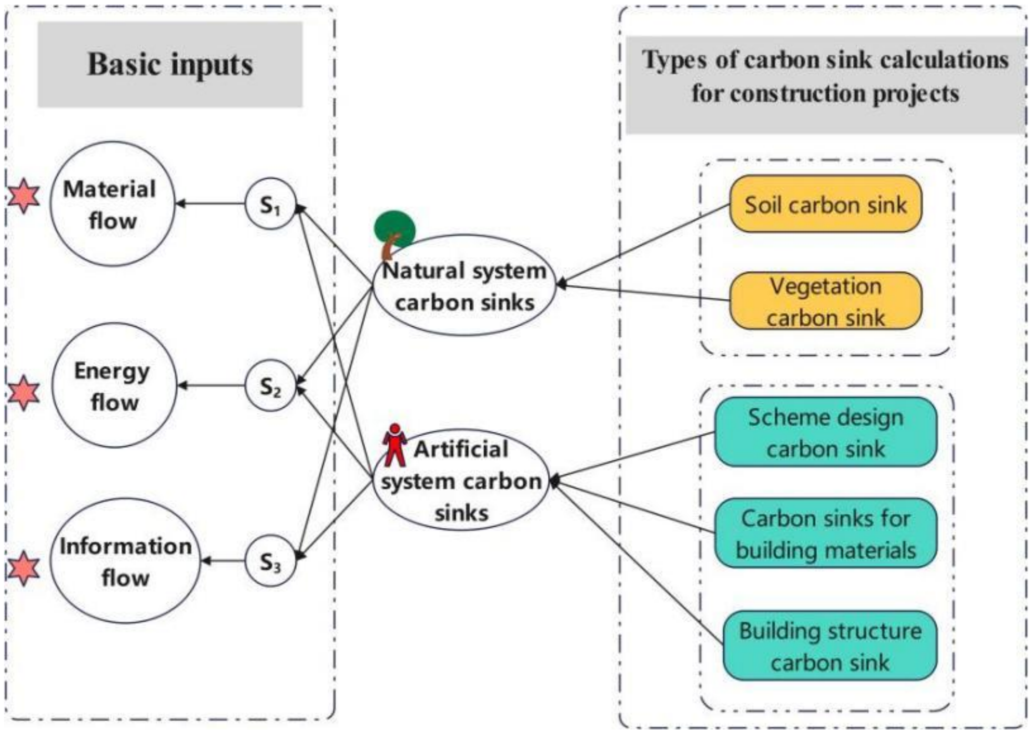

Figure 4. Landscape system carbon emission frame diagram.

Table 1. Carbon sink calculation list.

Method Types	Equations	Explanations
Soil type method	$T_{jd} = \sum_{i=1}^{k} \rho_i P_i D_i (1 - S_i)$ $M_d = \sum_{j=1}^{k} A_j T_{jd}$	ρ_i is the soil weight; P_i is the average organic carbon storage; D_i is soil thickness; S_i is the average gravel content. A_j is the area of a grid cell, T_{jd} is the unit mean organic carbon density; n is the total soil area grid units.
Life zone method	$B_D = b_0 + b_{1D} + b_2 \lg C_f$ $C = C_f + B_D(1 - \delta_2)V$	B_D is the soil weight; b_1, b_2, b_3 is the constant of soil weight and carbon density under different vegetation types; D is the depth from the surface to the center of the soil layer; C_f is the organic carbon mass fraction. $\delta_{2\text{mm}}$ is the gravel fraction; V is the soil layer volume.
Remote sensing technology method	$C_i = 0.58 S_i \sum (H_j Q_j W_j)$	i is the soil type; C_i is the soil organic carbon storage (t); 0.58 is the carbon storage conversion factor; S_i is the soil area; H_j is the mean soil thickness; Q_j is the average mass fraction of soil organic matter; W_j is the average soil weight.
Classical concrete carbonation theory	$d = \sqrt{\frac{2D_{CO_2} C_0}{m_0}} \cdot \sqrt{t}$	d is the concrete carbonation depth; D_{CO_2} is the effective diffusion coefficient of carbon dioxide in concrete; C_0 is the concentration of the concrete surface; m_0 is the carbon dioxide absorption per unit volume of concrete; t is the carbonization time.

2.4. Artificial Neural Network Method

Artificial neural network models can be used to predict and analyze the changing trends in ecological sustainability of landscape engineering. By training the model with historical data, it can learn patterns and trends related to the ecological sustainability of landscape engineering. Subsequently, the model can be utilized to forecast future trends and provide recommendations on how to improve or maintain ecological sustainability. It is important to note that the predictive capability of artificial neural network models is influenced by factors such as data quality, feature selection, and model parameters. Hence, during predictive analysis, ensuring the accuracy and representativeness of data and conducting appropriate tuning and validation of the model are crucial to enhance the reliability and accuracy of the prediction results.

Figure 5 illustrates the implementation steps and pathway of the neural network. Figure 6 represents the basic prediction model of the neural network.

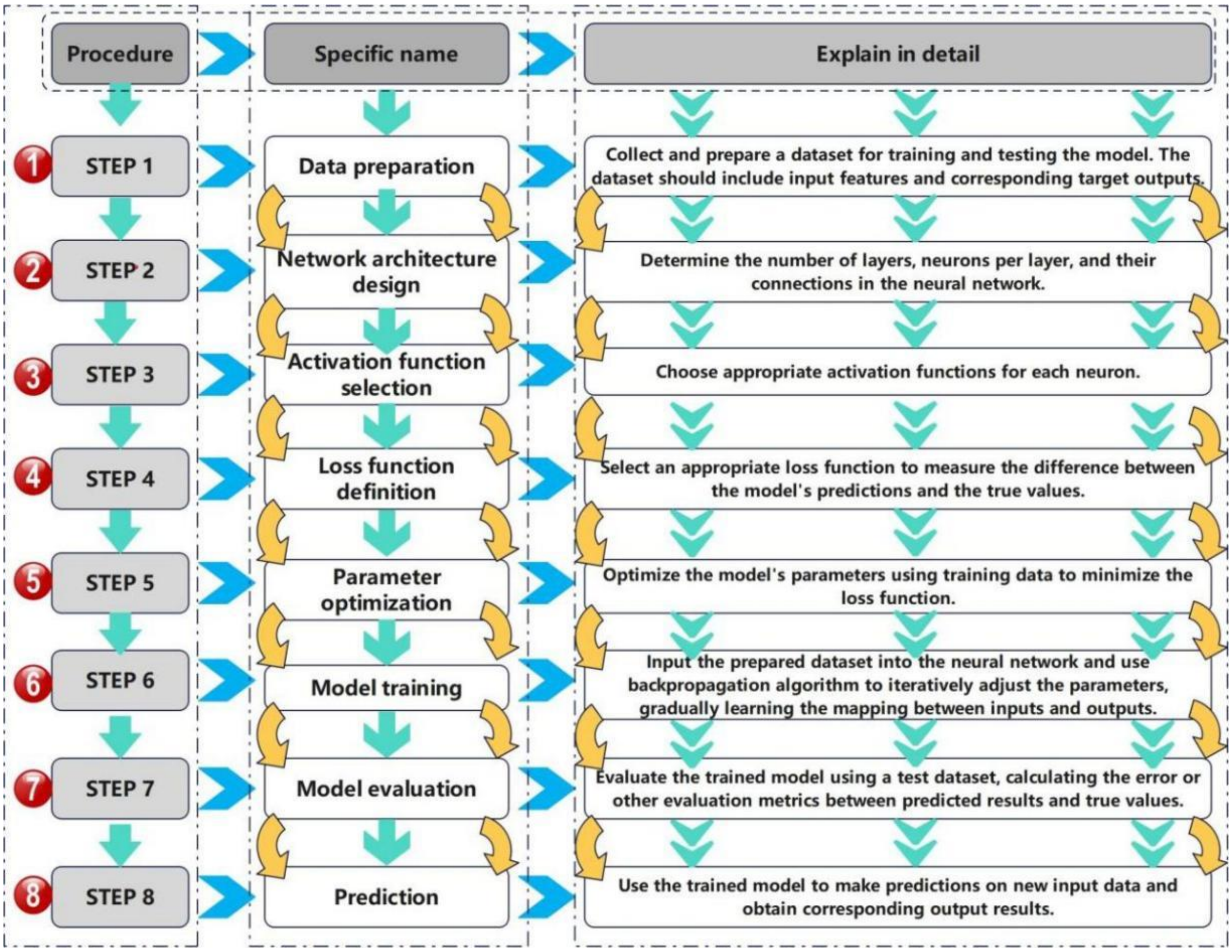

Figure 5. Artificial neural network implementation path diagram.

This study involves a significant amount of data statistics, which is crucial for the accuracy of the research methods. Analyzing from the perspectives of ecological emergy and carbon footprint methods, both require a comprehensive life cycle inventory of the research system, which poses some challenges for this study. Additionally, evaluating the accuracy of neural network prediction models is also a difficulty. As the number of hidden layers increases, the overall accuracy of the prediction model will vary, thus influencing the research results of this study.

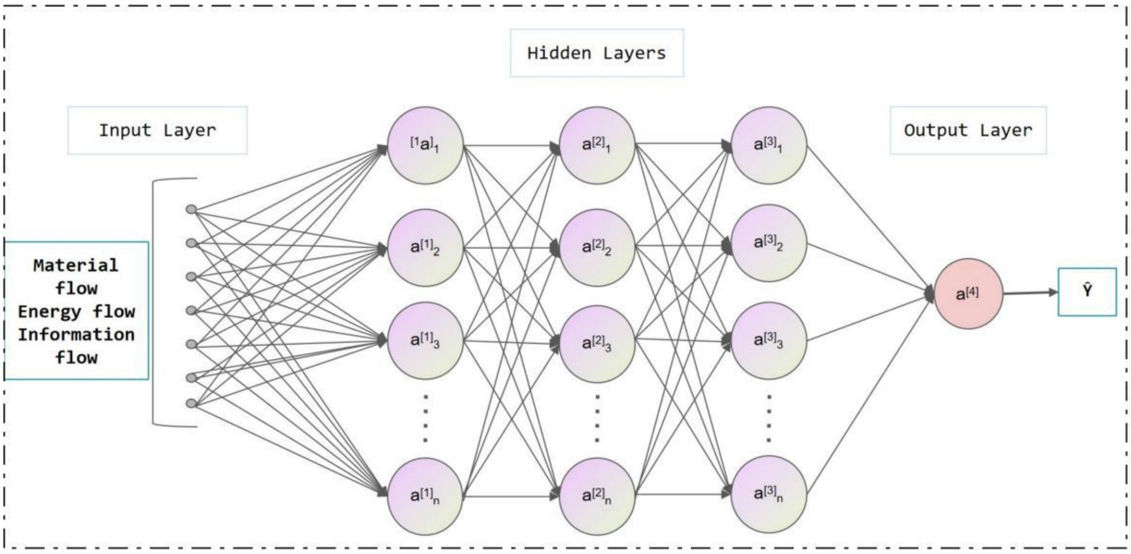

Figure 6. Neural network prediction model diagram.

2.5. Data Identification and Collection

The entire landscape renovation project involves multiple types of data, including material inventory data, energy inventory data, labor input data, etc. This article also involves information flow-related data, which has a crucial impact on analyzing the ecological transformation of the entire landscape. Figure 7 illustrates the process of data collection and selection.

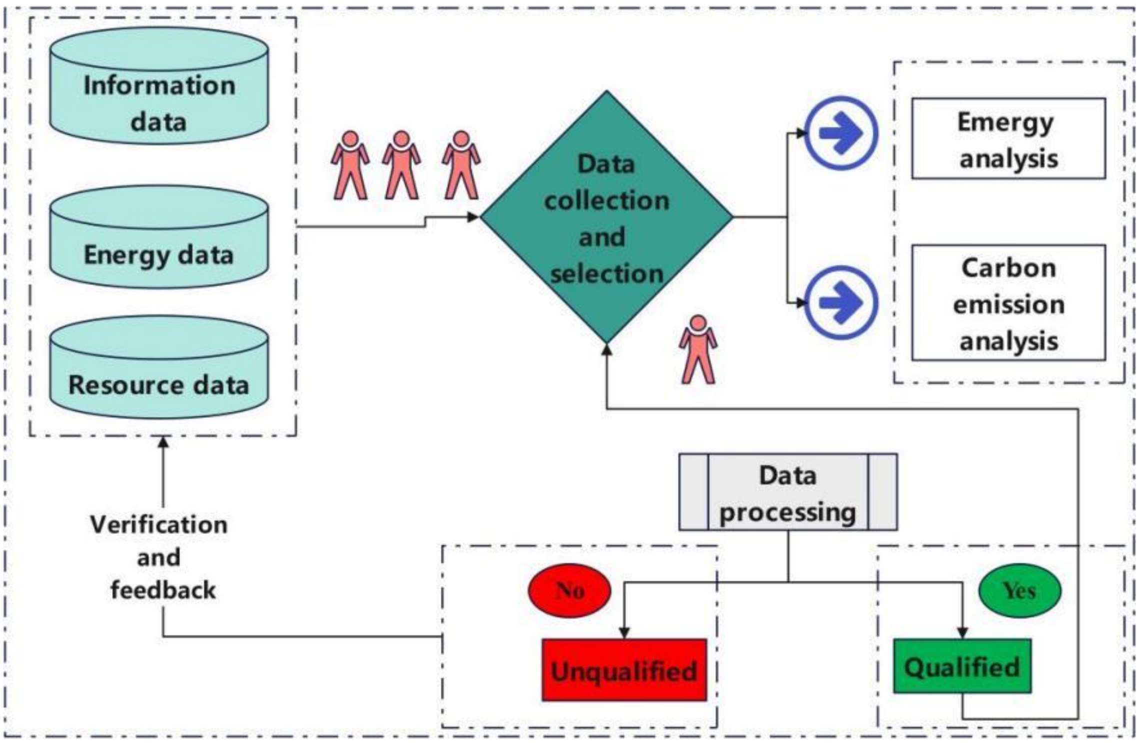

Figure 7. Data selection pathway diagram.

The importance of data filtering lies in its ability to help us extract useful information from a large volume of data, enabling decision-making and insights. For instance: improving data quality: data filtering eliminates invalid, erroneous, or duplicate data, ensuring the reliability and accuracy of the analyzed data set. Reducing noise and redundancy: by filtering data, it is possible to reduce the impact of noise and redundant information, leading to clearer and more credible analytical results. Saving time and resources: data filtering allows for the exclusion of irrelevant or unnecessary data, saving time and resources involved in processing and analyzing data. Discovering hidden patterns and trends: by filtering and focusing on specific subsets of data, it becomes easier to uncover hidden patterns, trends, and correlations within the data. Supporting decision-making: carefully filtered data can provide strong evidence for decision-making, reducing decision risks, and guiding organizational actions in market, operational, and strategic aspects. In conclusion, data filtering is a crucial step to ensure the effectiveness and accuracy of data analysis. It improves data quality, saves time and resources, and supports decision-making.

3. Case Study

Case Introduction

This case is located in Nanjing, Jiangsu Province, China. In order to enhance the urban living environment and promote ecological sustainability, a portion of the river landscapes has been redesigned. The selected rivers mainly focus on the main channel of the Jinchuan River, with a total length of approximately 50 km. The overall condition of the buffer zones on both sides of the river varies greatly, with limited space for landscape design and being mostly in a neglected state. From a landscape design perspective, the design of the riverbanks is monotonous, with a single type of planting, and lacks distinctive features. Table 2 and Figure 8 summarize the current status of waterfront greening in selected sections of the river (a total of nine river locations). Figure 9 shows a diagram of node changes in the river channel before and after landscape design.

Table 2. The current status of waterfront greening in selected sections of the river.

No.	Name	Length (km)	Waterfront Greening Status
1	Neijin River mainstream	2.88	Most of the waterfront areas have been restored as leisure green belts, with widths ranging from 2 to 10 m. The overall landscape greening quality is high, with lush vegetation along the riverbanks. Deciduous and shrub tree species are combined with riparian aquatic plants. Along the riverbanks, the use of stacked stones and faux wood pilings creates an environment for the growth of aquatic plants, achieving a unified combination of esthetics and ecology.
2	Neijin River east tributary	2.22	With the exception of small-scale riverside buildings in certain areas, most of the waterfront leisure green belts have been restored, with widths ranging from 2 to 5 m. The green belts along the riverbanks are generally connected, dominated by single rows of tall trees, with a linear and relatively simple hierarchy.
3	Neijin River central tributary	1.42	The green belts are discontinuous, with some sections lacking sufficient space along the river channels, resulting in the absence of waterfront green belts. Some sections of the rivers have abundant green spaces on both sides, with rich vegetation and pleasant walking experiences.
4	Neijin River central tributary	1.27	Apart from small-scale riverside buildings in specific locations, most of the waterfront leisure green belts have been restored. However, due to the dense surrounding residential areas and narrow landscape spaces along the river channels, it is not possible to form large-scale waterfront green belts. The width typically ranges from 2 to 5 m. Some sections of the rivers lack softscape due to their proximity to residential areas, parking lots, etc. The green belts along the mainstream of the Neijin River are intermittent, featuring linear and monotonous plant landscapes, and they lack connections with surrounding parks and green spaces.

Table 2. *Cont.*

No.	Name	Length (km)	Waterfront Greening Status
5	Northwest City Moat	1.16	The two sides of the waterfront leisure green belts are mostly connected, with widths ranging from 2 to 10 m. The combination of riverside landscapes and public green spaces creates an overall high-quality open space. While meeting the basic greening requirements along the entire line, attention is paid to the arrangement of tall trees, shrubs, and grass layers, creating a pleasant and high-quality walking and recreational experience.
6	North City Moat	1.13	The two sides of the waterfront leisure green belts are mostly connected, with widths ranging from 2 to 10 m. The overall quality of greening is high, with reasonable arrangements of tall trees, shrubs, flowers, and plants. The vegetation is well-distributed, creating a beautiful and pleasant riverside recreational space with rich layers, vivid colors, and distinct seasonal changes.
7	South Ten-Mile Long Ditch mainstream	0.93	Most of the waterfront leisure green belts have been restored, but there are significant differences in the current state of waterfront greening across different sections of the rivers. The river section in Yuanyuan Residential District has a purely hard landscape with a lack of softscape, while the river section near Hongshan Zoo Station has a good landscape environment with well-planned arrangements of tall trees, shrubs, flowers, and plants.
8	Zhang Wang Miao Ditch	0.86	There are significant differences in the current state of waterfront greening across different sections of the rivers. The section from Jianning Road to Mufu South Road is adjacent to a major road without any greenery. The section along Jinbi Road has a rich variety of green plants and shows healthy growth.
9	Waijin River	0.79	Most of the waterfront leisure green belts have been restored, with widths ranging from 2 to 10 m. The spaciousness of the waterfront leisure green belts allows for abundant vegetation with diverse colors that change noticeably throughout the seasons.

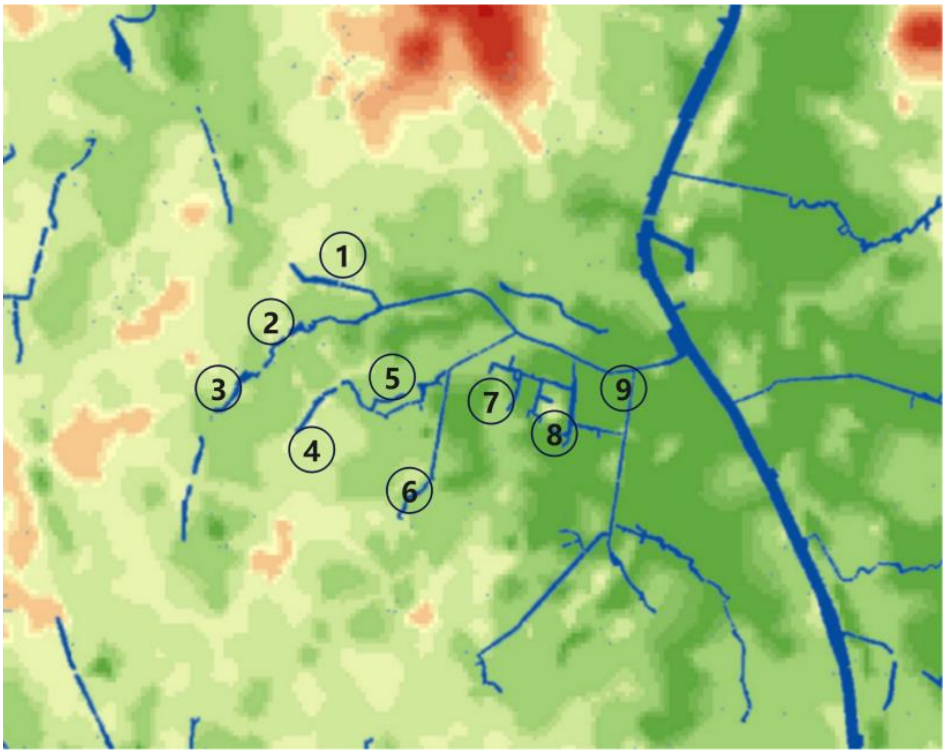

Figure 8. The research location of a river object.

Figure 9. Changes before and after landscape design.

4. Results and Discussion

The entire landscape engineering transformation process can be divided into five stages: the design stage, building material production stage, transportation stage, construction stage, and maintenance stage. By analyzing the emergy and carbon emissions throughout the five stages of the life cycle, the ecological sustainability of the entire landscape transformation system can be assessed. Additionally, by using a neural network prediction model, long-term ecological sustainability analysis of landscape engineering can be conducted.

Due to the large scale of the urban riverfront in the city, three specific locations have been selected to conduct a comprehensive life cycle analysis of emergy and carbon emissions for three small-scale landscape projects.

4.1. LCA–Emergy Analysis

4.1.1. Dominated Contributor

Taking the Neijin River mainstream landscape renovation project (Project No. 1) as an example, the emergy ratios across five stages are calculated and displayed for analysis. The time points chosen for analysis are the first year and the 20th year of operation. Figure 9 provides a clear view of the emergy changes in each stage.

From the perspective of the entire life cycle, Figure 10A depicts the emergy distribution of five stages of landscape engineering operations over one year. Material-related emergy has the highest contribution, accounting for approximately 49%. Construction comes next, representing 23% of the total. The other three stages have a smaller impact and are considered secondary. In Figure 10B, which simulates the operation of the landscape project over 20 years, it is evident that the emergy proportion during the entire operational phase reaches 75%, significantly higher than the other four stages. This indicates that the ecological sustainability of the entire landscape system requires continuous maintenance, including a constant input of material flow, energy flow, and information flow. Consequently, the proportion of emergy in the maintenance stage keeps increasing.

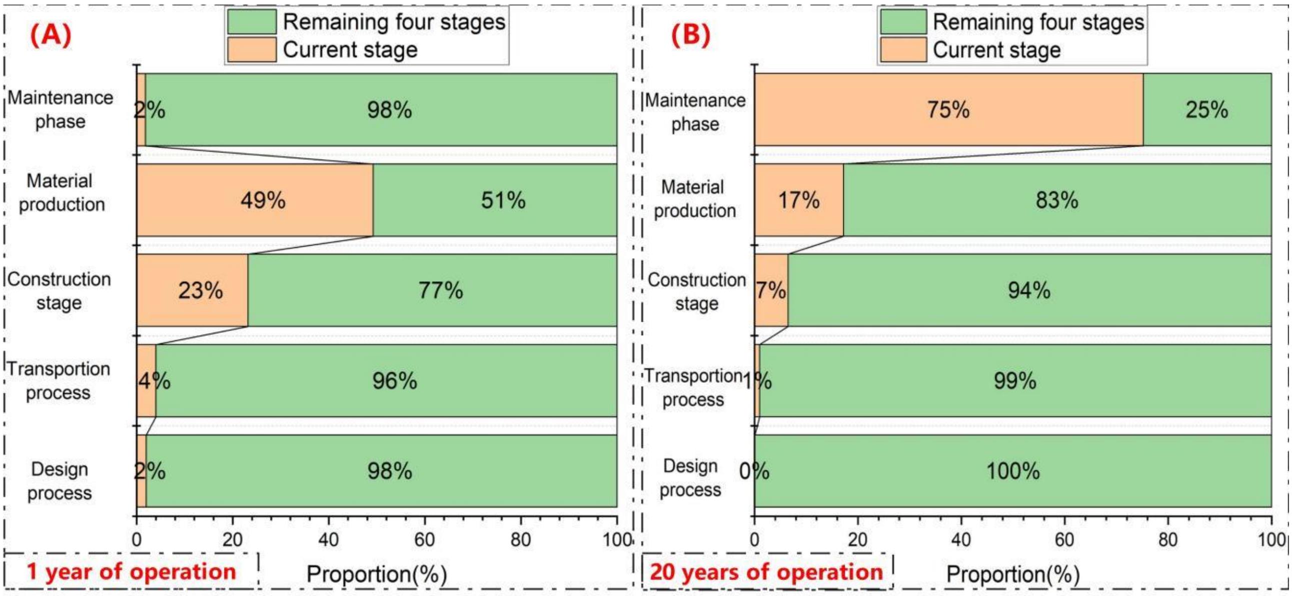

Figure 10. Contribution proportion of five stages. (**A**) Proportion of operation for one year. (**B**) Proportion of operation for twenty years.

4.1.2. Emergy Indicator Analysis

Using No. 1 project as an example (Table 2), the sustainability indicators were simulated for three periods: a 10-year cycle, a 20-year cycle, and a 30-year cycle. Figure 10 illustrates the changes in the indicators at these three time points. From Figure 11, it can be observed that the EYR (Energy Yield Ratio) decreases over time, indicating a decreasing emergy production efficiency of the entire landscape system and a tendency toward decline. Conversely, analyzing the Environmental Load Ratio, which increases continuously from 132.8 to 238.6, indicates a gradual increase in the environmental cost of operating the landscape system. Based on the assessment of the emergy production rate and environmental load ratio, the Energy Sustainability Index (ESI) is quantitatively calculated. The ESI for the landscape system operating for 10 years is 0.335, reducing to 0.212 after 20 years and further declining to 0.109 after 30 years. This implies that the landscape system requires reconstruction or major refurbishment.

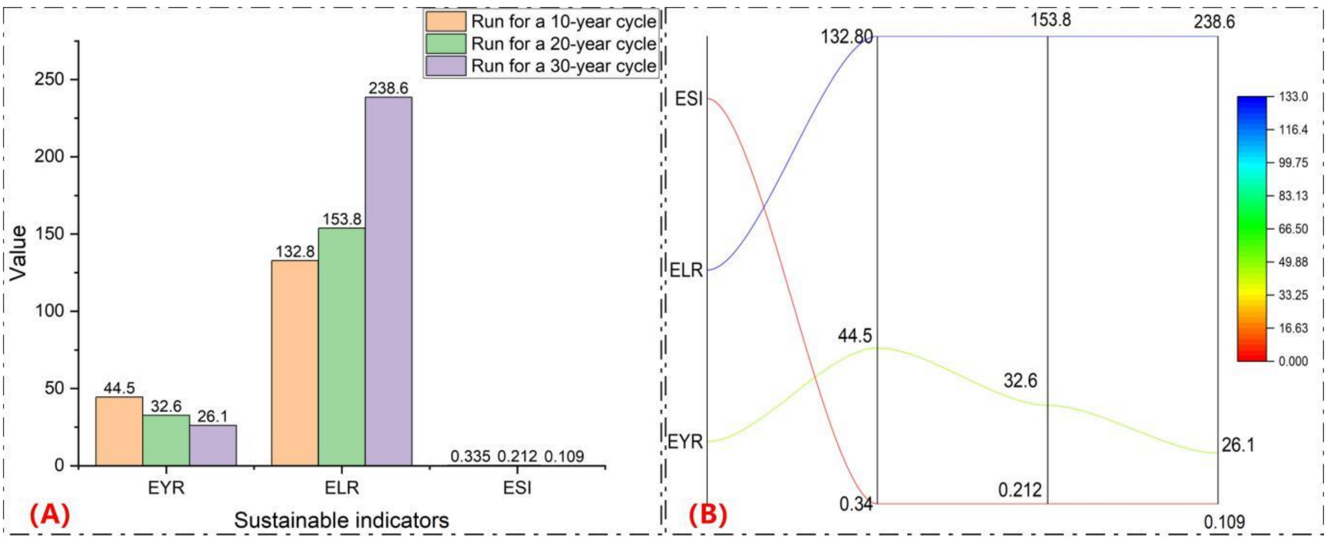

Figure 11. Sustainable indicator comparisons. (**A**) Sustainable indicators. (**B**) Comparative analysis.

4.1.3. Sensitivity Analysis

Data uncertainty analysis is a crucial step in understanding and assessing uncertainties within data. It aids decision-making, model evaluation, information communication, and risk management, thereby enhancing the accuracy and reliability of data analysis.

To quantitatively demonstrate the sensitivity of data using EYR (Economic Yield Ratio), ELR (Energy Loss Rate), and ESI (Emergy Sustainability Index) as core indicators, we can analyze the following hypotheses:

Hypothesis 1. *Basic data fluctuates by 10%, including material flow data, information flow data, energy flow data, etc.*

Hypothesis 2. *The energy conversion rate fluctuates by 5% to examine the sensitivity changes of the three indicators.*

Figure 11 presents the sensitivity trends of nine landscape engineering (Table 2) sustainability parameters.

Figure 12 presents the sensitivity results, showing that the first three types of landscape renovation project result in minor changes in sustainable parameters, as depicted in Figure 12 (No. 1/No. 2/No. 3). Taking the ESI parameter as an example, the fluctuation ranges are 8.47% and 4.31% for Scenario 1 and Scenario 2, respectively. However, the middle three items (No. 4/No. 5/No. 6) exhibit significantly increased fluctuations, with ESI changes of 11.6% and 7.29%, respectively. The last three landscape renovation projects (No. 7/No. 8/No. 9) have fluctuations ranging from 8% to 12%.

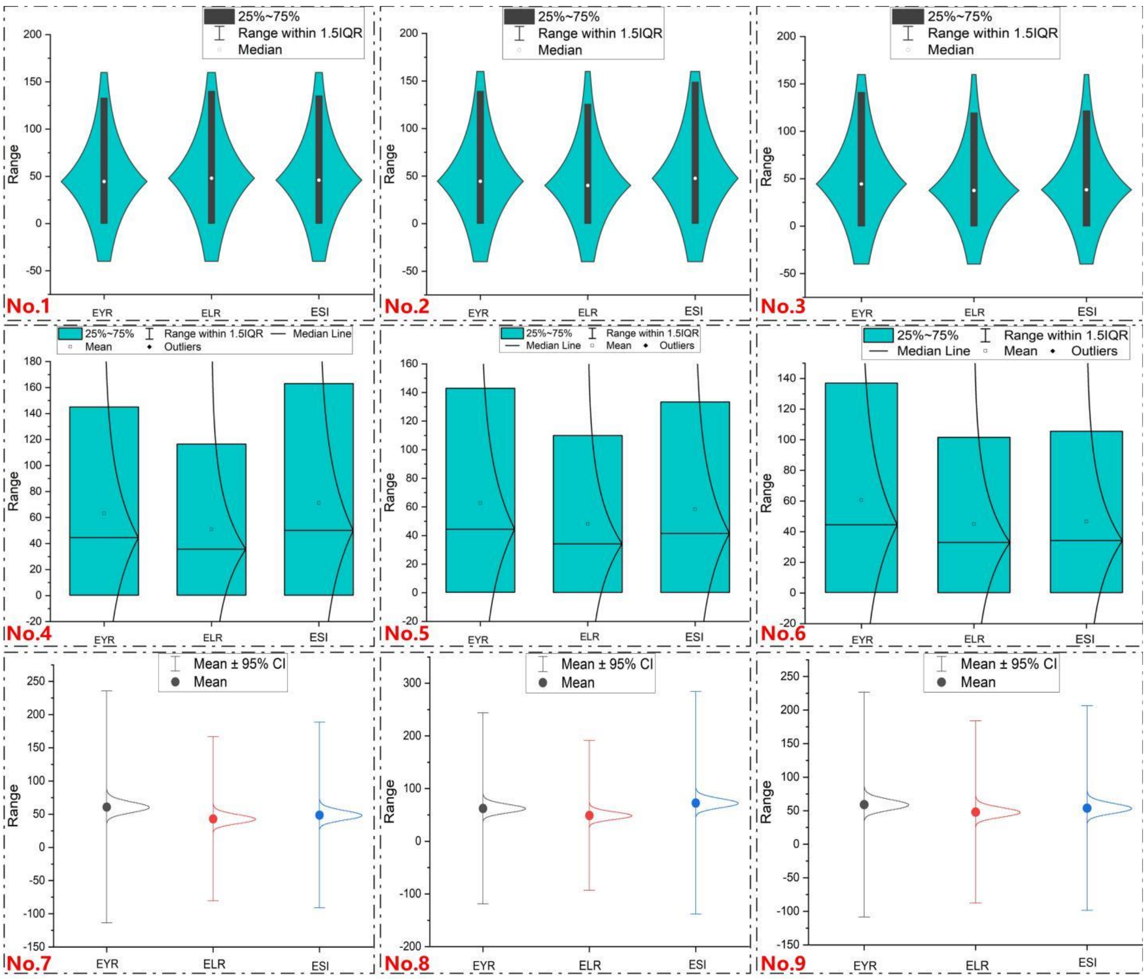

Figure 12. Sensitivity changes under Hypotheses 1 and 2.

As the proportion of assumed data fluctuations increases, the final variation in sustainable indicators also increases. Additionally, in situations with a smaller sample size, the sensitivity is more pronounced, and the impact received is greater.

4.2. LCA–Carbon Emission Analysis

This chapter consists of two parts: carbon emission calculations for nine landscape renovation nodes, and calculation and validation of carbon sequestration effects.

4.2.1. Carbon Emission Analysis

In this section, the energy consumption of transportation (diesel fuel) is accounted for in the materials, totaling eight items. Figure 13 illustrates the carbon emission calculation results for nine landscape renovation nodes. From Figure 13, it is evident that diesel fuel has the highest carbon emissions, followed by cement, steel, and gravel. The other four materials (brick, lime, sand, and wood) contribute less to carbon emissions. Analyzing the nine types of renovation project, Project 1 has the highest carbon emissions from diesel fuel at 33.8 tCO_2, followed by cement at 26.6 tCO_2 and steel at 18.7 tCO_2. Due to the largest length of landscape renovation in Project 1, it has the highest consumption of materials and energy.

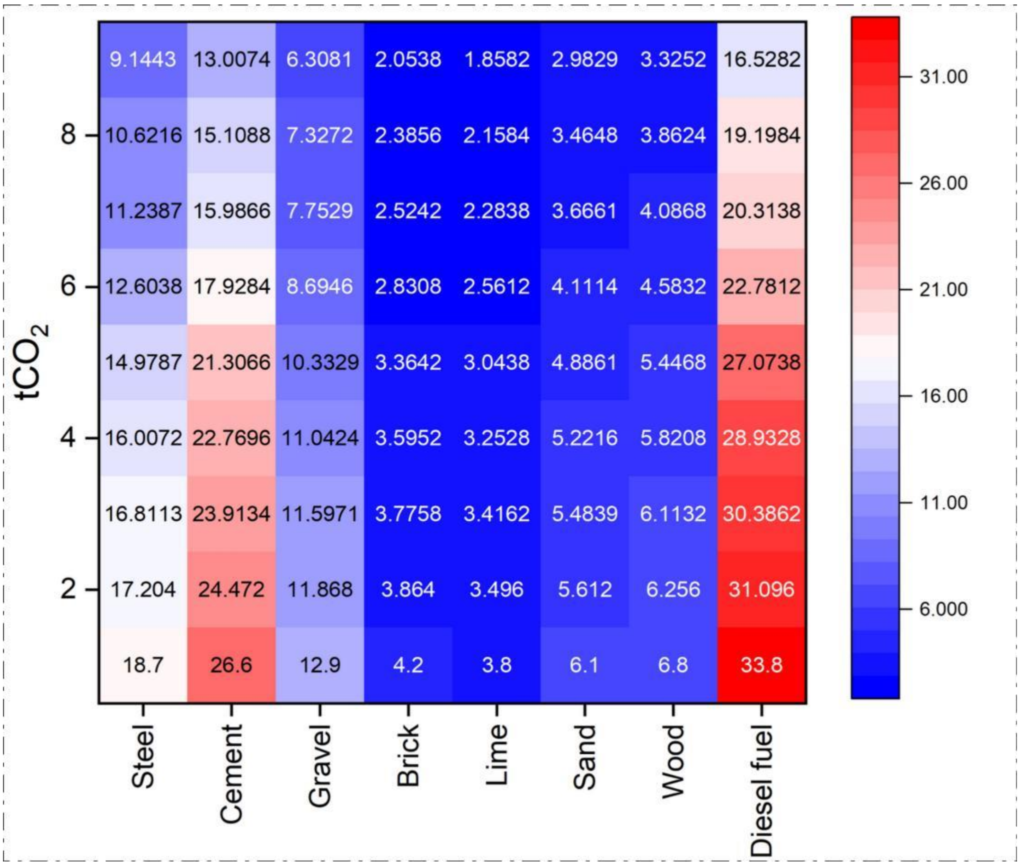

Figure 13. Presentation of carbon emissions from main materials and energy sources.

4.2.2. Carbon Sink Effect Analysis

Carbon sink calculations can help assess and determine the contribution of landscape renovation projects to carbon emission reduction targets. It quantifies the amount of carbon dioxide absorbed by projects through measures such as increasing vegetation coverage and improving soil quality, providing a basis for evaluating their environmental benefits. Carbon sink calculations can be used to evaluate the effectiveness of landscape renovation projects in adapting to climate change. By increasing vegetation and enhancing soil health, projects can enhance ecosystem resilience and reduce vulnerability to climate change.

Section 2.3 provides models for calculating four types of carbon sink, including soil carbon sinks and concrete material carbon sinks. Landscape systems are an important approach to mitigating climate change because they can absorb carbon dioxide through the elements planted within the landscape system, thereby reducing CO_2 levels in the environment.

Taking soil carbon sequestration as an example, the selected parameters are an average carbon concentration of 26.41 g/kg (1–20 cm) for riverbank soil and a carbon density of 3.98 kg/m^2. The regional variation coefficient is 0.48. Based on these parameters and the formulas from Section 2.3, the calculated annual carbon sequestration for soil is 2.46 tCO_2. Similarly, the carbon sink capacity of concrete (used for river embankments) can reach 5.63 tCO_2 per year. This demonstrates that the carbon sequestration potential of the entire landscape renovation project is significant and requires special attention and should not be ignored.

4.3. Neural Network Model Prediction Analysis

The neural network model can be used to predict and analyze the ecological sustainability of landscape engineering systems. In this section, taking the ESI index as an example, the predicted trends of the sustainability of the entire landscape engineering system over 10, 20, and 30 years are analyzed. Figure 14 illustrates the patterns of these changes.

Figure 14A shows the ESI indicator trends over a 10-year period, indicating an overall growth despite significant fluctuations in individual data points. This demonstrates that the landscape engineering system is in its early stage of development and is still in a sustainable state. Figure 14B presents the projected ESI trends over a 20-year period, showing a continued growth trend, although the rate of growth is diminishing. In Figure 14C, which represents the ESI indicator trends over 30 years, the landscape system is observed to be gradually declining. Although regular maintenance and small-scale renovations are implemented for the landscape system, the overall sustainability of the system decreases.

Neural network models can play a positive role in predicting the ecological emergy of building projects, similar to architectural engineering. While some scholars have conducted neural network evaluations for various aspects of building projects [43–46], research on the sustainable ecological energy value of landscape architecture is still in its early stages. This paper represents a forward-looking exploration of this aspect.

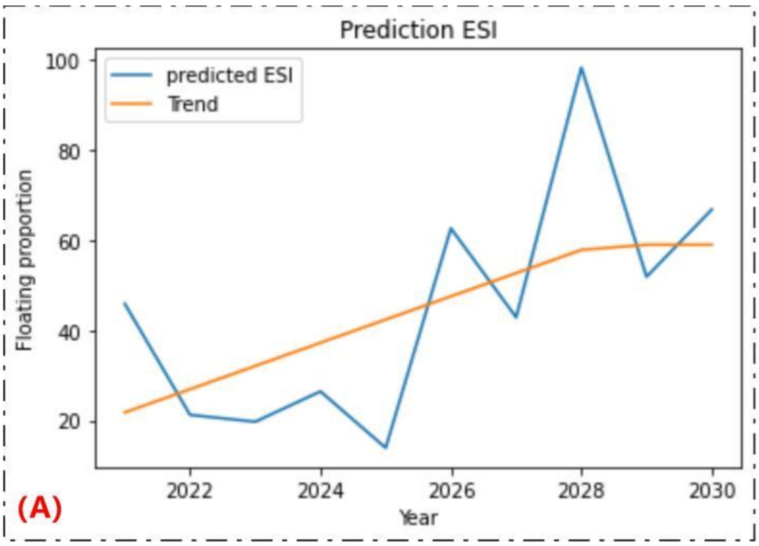

Figure 14. *Cont.*

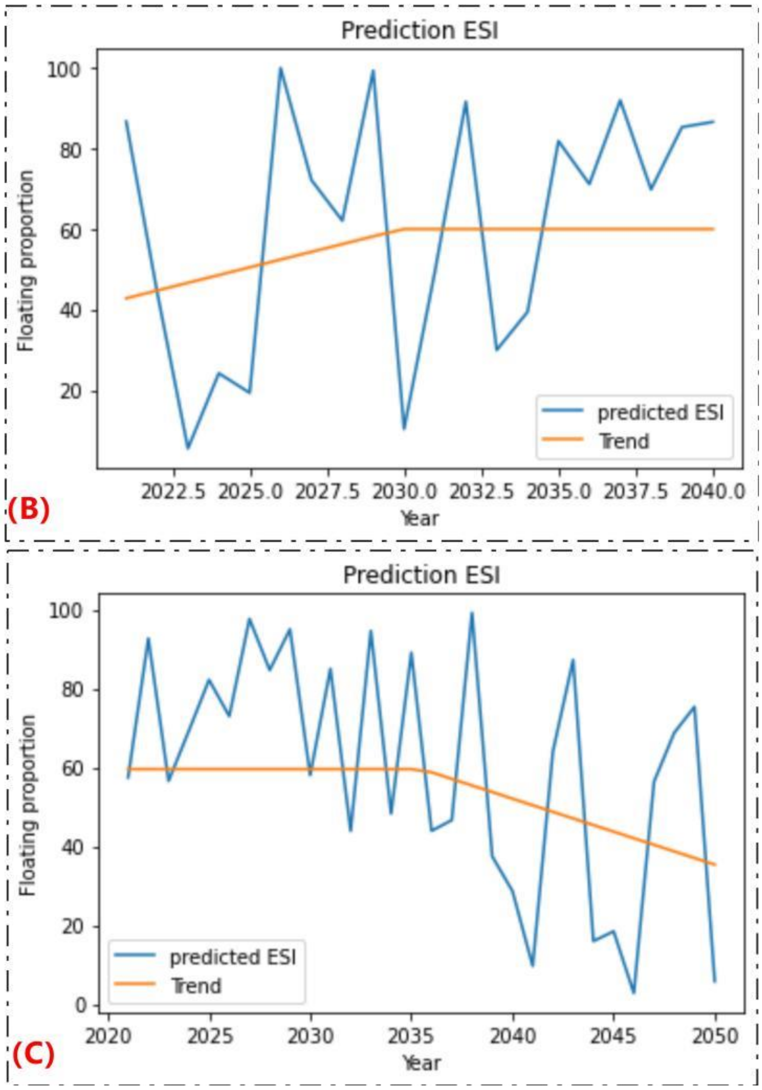

Figure 14. Predicted trends based on an ESI indicator. (**A**) Prediction of ESI parameters for 10 years. (**B**) Prediction of ESI parameters for 20 years. (**C**) Prediction of ESI parameters for 30 years.

Neural network systems can be used to predict the ecological emergy sustainability of landscape engineering. By collecting and analyzing relevant data, neural networks can learn and establish patterns to forecast the trends and sustainability of the ecological emergy in landscape engineering systems. These predictions can assist decision-makers in evaluating and optimizing the design, management, and maintenance of landscape engineering to achieve better ecological benefits and sustainable development. However, this requires appropriate training datasets, rational feature selection, and effective neural network architectures to ensure accurate prediction results and reliable decision support.

5. Landscape System Correction Strategy

According to the research in this article, the overall sustainability of the system needs to be improved from an ecological energy perspective. Furthermore, the efficiency of the entire system needs to be enhanced based on carbon footprint evaluation. This article attempts to improve the sustainability of the system from three aspects: sponge city system, coupling of sewage treatment subsystems, and optimization of landscape engineering system efficiency. By implementing these three enhancement measures, the sustainability of the waterfront landscape system can be improved to some extent, providing valuable reference for urban managers.

The concept of a sponge city Is a planning and design approach aimed at addressing water resource management and environmental issues in urban areas. This concept emphasizes transforming cities into sustainable entities that can absorb, store, and utilize rainwater by mimicking the functions of natural ecosystems. The advantages of a sponge city include reducing the risk of flooding, improving urban microclimates, enhancing water resource utilization efficiency, increasing urban green spaces and ecological functionality, and improving residents' quality of life. This concept has been widely applied in many cities and has become an important strategy for tackling climate change and promoting urban sustainability.

A wastewater treatment system is a facility and process used to treat wastewater generated from urban, industrial, and rural areas. Its purpose is to remove or reduce harmful substances in the wastewater to an acceptable level in order to protect the environment and public health. The implementation of wastewater treatment systems helps to reduce water resource pollution, improve environmental quality, and protect public health. This concept is widely applied in urban and rural areas to ensure sustainable water resource management and protection.

A landscape engineering information flow monitoring system is a facility and technology used to collect, analyze, and monitor information flows related to landscape engineering projects. The implementation of the landscape engineering information flow monitoring system helps landscape engineering teams and relevant stakeholders gain an in-depth understanding of public attitudes, feedback, and demands regarding projects for effective project management, public sentiment handling, and decision-making.

5.1. Coupled Design of the Sponge City Concept

The sponge city design approach enhances the sustainability of waterfront landscapes through several key elements. Firstly, it focuses on effective stormwater management by integrating green infrastructure such as permeable pavements, rain gardens, and bioretention areas to absorb and filter rainwater, reduce runoff, and improve water quality. Secondly, sponge city design promotes the protection and restoration of natural ecosystems in waterfront areas. This includes creating wetlands, riparian buffers, and green spaces that provide habitat for wildlife and serve as natural filtration systems for water bodies. Additionally, the design approach encourages the use of sustainable materials and technologies in construction and development. This includes adopting energy-efficient techniques, utilizing recycled materials, and implementing low-impact development practices to minimize environmental impact. By implementing these strategies, sponge city design enhances the resilience and long-term sustainability of waterfront landscapes, ensuring their ecological integrity and promoting a more sustainable and livable urban environment. Figure 15 illustrates the implementation pathway of the sponge city design approach.

The main improvement measures in this section involve selecting three types of sponge city practice. Firstly, the hierarchical landscape drainage system (Figure 15A–C) is implemented to intercept materials from reinforced cages filled with broken stones (naturally sourced) and set up water discharge gates with varying elevation differences using gravity. The reinforced cages can filter some large particle pollutants in wastewater, thereby improving water quality to a certain extent. At the same time, planting vegetation inside the reservoirs (Figure 15A,B,E,F) helps in automatically purifying the water and further enhancing the sustainability of the water system. Additionally, to filter the water entering the river from both sides, a cascading landscape design can be established along the riverbanks, serving the dual purpose of mitigating urban river overflow and purifying the water quality entering the river (Figure 15D).

To validate the specific effects, an emergy estimation was conducted for the landscape renovation project of Project 1 (Table 2). If the design approach of the sponge city is adopted, there will be a significant increase in the overall engineering quantity of the landscape system. Initially, it may require substantial investment. However, as the usage period increases, based on the ecological emergy index ESI calculation, the overall sustainability of the landscape project can be improved by approximately 15% (from ESI = 0.335 to 0.385). The efficiency of this aspect has been confirmed by relevant scholars. For specific details, please refer to references [45–47].

Figure 15. Exhibition of sponge city design elements. (**A**) Water purification system. (**B**) Single-layer water purification system. (**C**) Components of a natural water purification system. (**D**) Step-style purified water landscape. (**E**) Water purification collection pool. (**F**) Landscape pathway.

5.2. Sewage Purification System

Wastewater treatment systems can effectively purify the water of urban rivers. These systems employ a series of physical, chemical, and biological processes to remove suspended solids, organic substances, nutrients, and harmful substances from wastewater. Firstly, wastewater undergoes primary treatment where solid residues are removed and settled. Next, the wastewater enters secondary treatment, utilizing biological methods such as activated sludge or anaerobic digestion to eliminate organic matter and nutrients. During this process, bacteria and other microorganisms decompose organic matter, thereby reducing the pollutant content in the water. Finally, the wastewater undergoes advanced treatment to remove residual organic matter, nutrients, and microorganisms. Common methods for advanced treatment include biofiltration, biogas fermentation, and ozone oxidation. These processes further purify the water quality, ensuring compliance with environmental standards and sustainable development requirements. The water treated by the wastewater treatment system is then discharged into urban rivers, significantly improving their water quality. This helps protect aquatic ecosystems, provide clean water resources, and reduce adverse impacts on the environment and human health. However, continuous monitoring and effective maintenance are crucial to ensure the proper functioning and safety of wastewater treatment systems.

Figure 16 depicts the basic flow path and key nodes of a wastewater treatment system. Taking the ESI (Ecological Sensitivity Index) as an example, coupling wastewater treatment with landscape engineering systems significantly enhances ecological sustainability, increasing it from 0.335 to 2.41, representing an approximately 7.19-fold improvement. However, this calculation does not consider the various inputs required by the wastewater treatment system; it only focuses on the positive effects of integrating the wastewater treatment system into the landscape engineering.

Studies conducted by relevant scholars regarding the impact of wastewater treatment systems on urban river water quality have been validated and shown to have significant effectiveness in greatly enhancing the sustainability of urban rivers [48,49]. However, their shortcomings are also evident, namely the requirement for a substantial investment and the need for assessment as a subsystem of the entire urban system.

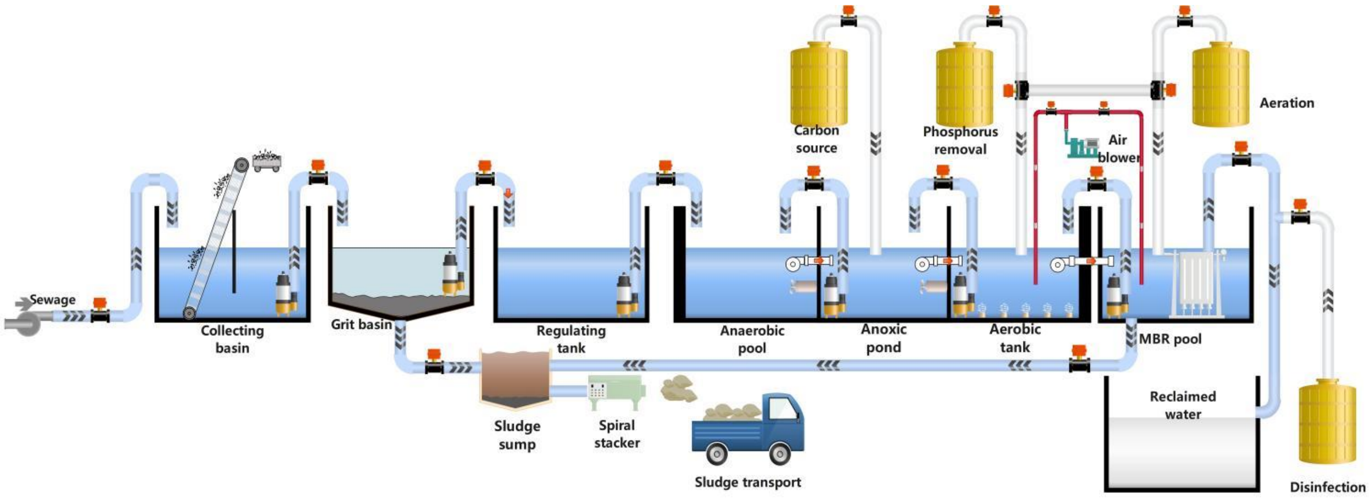

Figure 16. Sewage treatment system.

5.3. Information Flow Optimization Control System

In order to enhance the intelligent management level of landscape engineering, a complete monitoring, detection, and control topology diagram is designed and applied. Figure 16 represents the topology control system diagram. The entire process involves data collection from cameras, detectors, sensors, and probes, which is then collected and processed by regional servers. The data are uploaded to a central processing computer for data analysis, providing managers with appropriate recommendations.

The smart landscape topology diagram is a visual representation of the interconnected components and systems that make up a smart landscape. It illustrates the structure and relationships between various elements such as sensors, actuators, controllers, data networks, and management systems. At the center of the topology diagram is typically a central control hub or server that serves as the core of the smart landscape system. This hub receives data from different sensors distributed throughout the landscape, such as weather sensors, soil moisture sensors, light sensors, and motion sensors. The central control hub processes and analyzes the collected data in real time. Based on the analysis results, commands and instructions are sent to actuators and devices distributed across the landscape. These devices can include irrigation systems, lighting fixtures, water pumps, and other infrastructure components. The smart landscape topology diagram also depicts the communication infrastructure used for seamless data transmission and exchange between different components. This may involve wired or wireless networks, including local area networks (LANs), wide area networks (WANs), and Cloud-based platforms. Overall, the smart landscape topology diagram provides an overview of how different components within the system are connected and interact to create an intelligent and efficient management system for landscapes. It helps stakeholders understand the flow of information, control mechanisms, and the overall architecture of the smart landscape solution.

According to the design and application of the topology diagram in Figure 17, the information flow within the entire landscape system is more efficient, avoiding ecological landscape damage caused by information delays. Taking the ESI index as an example, the use of the complete monitoring system greatly increases the proportion of emergy in the information flow. In this study on landscape ecology in design engineering, ESI can improve efficiency by approximately 25% (from 0.335 to 0.268).

Similarly, there is a limiting negative factor. Due to the higher cost associated with the overall automated monitoring system, when converted into ecological costs, it has a significant negative impact in the early stages of landscape projects. The positive effects can only become evident as the lifecycle of the landscape project is extended. Relevant scholars have also studied the effectiveness of information flow topology [50,51].

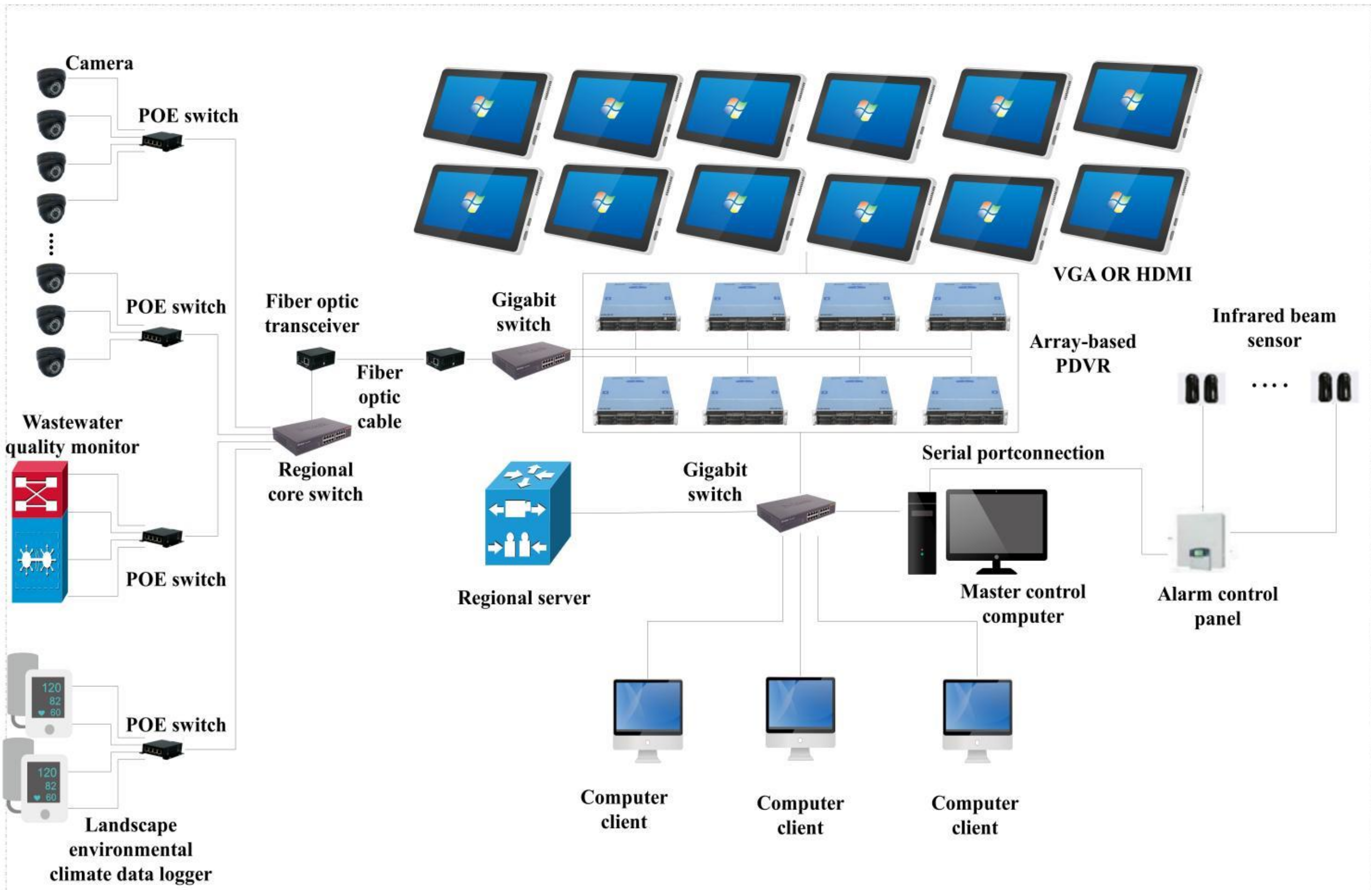

Figure 17. Coupling design of a landscape engineering monitoring system.

6. Discussion on the Comparison with Other Studies

Sustainability research on urban waterfront landscapes is a hot topic, especially regarding the influencing factors, including water bodies, landscapes, slopes, and management [52–56]. Specifically, different researchers have analyzed and discussed this type of research from various perspectives.

For example, some researchers investigate the energy efficiency of different design strategies for urban riverfront landscapes and propose sustainable approaches to reduce energy consumption [57]. Several authors evaluate the carbon emissions associated with urban riverfront development in two cities and identify potential mitigation measures to enhance sustainability [58]. By using life cycle assessment to analyze the environmental impacts of green infrastructure, interventions in urban riverfront redevelopment, focusing on energy use and carbon emissions, have been realized [59]. From the view of the importance of incorporating green spaces into urban planning for carbon reduction, the research [60] assesses the carbon sequestration capacity of riverfront parks in an urban context, emphasizing the importance of incorporating green spaces into urban planning for carbon reduction. A study examines energy-efficient design strategies applied to urban riverfront landscapes, highlighting successful practices and lessons learned from a case study in GHI city [61].

Compared to previous studies, this article conducts an assessment and research on the sustainability of waterfront landscapes from the perspective of the entire life cycle's emergy and carbon emissions. Specifically, focusing on urban river scenarios, an estimation is made of their ecological emergy and carbon emissions, providing new insights for urban ecological sustainability research.

7. Conclusions

To verify the ecological sustainability of urban river landscape systems, this study applies the whole life cycle emergy and carbon emission methods to landscape renovation projects. Additionally, through the prediction of artificial neural networks, a long-term assessment of the ecological sustainability of landscape projects is conducted.

From the perspective of ecological emergy, in the long term, landscape engineering's ecological maintenance emergy accounts for approximately 75% and is a major influencing factor. Over time, the three main indicators (EYR/ELR/ESI) show varying degrees of change, especially the emergy sustainability parameter ESI, which serves as a core reference indicator, exhibiting a decreasing trend. This indicates that as time goes on, the landscape system gradually becomes less efficient. Analyzing carbon emissions from nine types of landscape node, diesel fuel, cement, steel, and other factors were identified as the main contributors to carbon emissions. At the same time, a quantitative estimation of the landscape system's carbon sink was conducted, which helps to clearly identify and understand the carbon emissions of the entire landscape system. This is beneficial for urban managers in implementing low-carbon management.

To enhance the ecological sustainability of the entire landscape system, three types of improvement measure have been preliminarily designed and applied. These include sponge city design enhancement pathways, coupled wastewater treatment systems, and optimization of information flow. From the effectiveness perspective, these measures have a certain positive impact on the landscape's ecological sustainability as described in this article. However, all three improvement measures require relatively high investment costs, especially the coupling of wastewater treatment modes and information flow monitoring systems. The selection of these measures should be based on the type and pattern of different ecological landscapes.

In addition, this study needs to consider the continuity of waterfront landscapes, especially their ecological impact on the entire urban system. This is an area that requires in-depth research. Moreover, due to the significant carbon sequestration effects of water systems, precise calculations at the carbon sink level are necessary to enhance the overall accuracy of the study. Therefore, the next research step should focus on these two aspects.

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