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Prediction of Life Cycle Carbon Emissions of Sponge City Projects: A Case Study in Shanghai, China

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Abstract: In recent years, China has been vigorously carrying out the planning and implementation of Sponge City. Since the implementation of Sponge City projects involves substantial materials and energy consumption, it is significant to account corresponding carbon emissions and sinks. The existed studies about carbon emission of stormwater management measures, however, are not able to take the whole life cycle and different facilities into consideration. Therefore, this study develops a comprehensive accounting model based on Intergovernmental Panel on Climate Change (IPCC) guidelines and life cycle assessment (LCA) method to predict carbon emissions and carbon sinks of Sponge City projects more comprehensively and accurately. The model is applied to an actual residential community in Shanghai as a case study. Results show that the total indirect carbon emission is estimated to be 774,277 kg CO_2 eq during a 30-year lifespan, among which carbon emissions from operation and maintenance phases are 2570 kg CO_2 eq/year and 7309 kg CO_2 eq/year, respectively, both directly proportional to the service life of the facilities. Three kinds of achievable carbon sinks are carbon sequestration in green space (5450 kg CO_2 eq/year), carbon sink from rainwater utilization (15,379 kg CO_2 eq/year) and carbon sink from runoff pollutant removal (19,552 kg CO_2 eq/year). Carbon neutrality is expected to be reached after approximately 19 years. The established carbon emission accounting model can contribute to better planning and construction of Sponge City in China and enhance further energy conservation and carbon emission reduction.

Keywords: residential community; Sponge City; carbon emission accounting; life cycle assessment (LCA); low impact development (LID); urban sustainability; building sustainability

1. Introduction

With the rapid development of urbanization, large quantities of pervious natural land in China has been replaced by impervious roofs and pavements. Meanwhile, heavy rainfall events are more and more frequent due to global climate change. Since it is difficult for imperious surface to infiltrate, retain and store runoff, urban areas are easy to be attacked by floods when large storm comes, threatening the safety and property of urban residents [1]. Under this background, China has been gradually and vigorously promoting the planning and construction of Sponge City since 2013, intending to mitigate urban floods, reduce non-point pollution, promote rainwater utilization and improve the urban microclimate and local environment [2–5]. Sponge City is a Chinese version of the urban stormwater management concept proposed to achieve better management and control of stormwater runoff, which is similar to best management practices (BMPs), low impact development (LID), green infrastructure (GI), and sustainable urban drainage system (SUDS) and water-sensitive urban design (WSUD), which all aim to achieve better management and control of stormwater runoff [6]. From a global perspective, sustainable development will also be a long-term trend in the future. In 2015, the 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals was adopted by the United Nations [7]. Among the 17 goals, there are several goals related to urban and building sustainability, including: Ensure healthy lives and promote wellbeing for all at all ages; Ensure availability and sustainable management of water and sanitation for all; Ensure access to affordable, reliable, sustainable and modern energy for all. In this case, the Sponge City strategy proposed and adopted by China is also greatly in line with global sustainable development trends and goals.

To improve global sustainability, China has strengthened its implementation of a carbon emission reduction plan and green economy strategy [8–10]. In order to explore the sustainable development path, almost all industries are required to take measures to conserve energy, reduce carbon emission and abate pollution. From the perspective of time, Sponge City planning and construction will coexist with carbon emissions reduction actions for a long time. In order to explore the sustainable development path, almost all industries are required to take measures to conserve energy, reduce carbon emission and abate pollution [11–16], it is also a vast and long-lasting engineering activity with substantial materials utilization, energy consumption and waste produced, making corresponding carbon emissions unable to be ignored. Moreover, the cleanliness and reasonable utilization and recycling of materials and energy, as well as potential carbon sinks, all have considerable impacts on total net carbon emission reduction [17–21], which can provide references for the proposing of carbon reduction measures. Therefore, it is crucial to analyze the approaches of carbon emissions and sinks from Sponge City facilities or low impact development—best management practices (LID-BMPs), in order to reduce the net emission to the minimum.

Up to now, some studies have been conducted to estimate the carbon emissions and sinks of stormwater management measures in recent few years. Flynn and Traver [22] conducted carbon emission accounting for both rainwater gardens and green roofs. Spatari et al. [23] used life cycle assessment (LCA) and a stochastic urban watershed model to account the avoided greenhouse gas emissions of permeable pavements corresponding to annual energy savings in America. Kim et al. [24] established a comprehensive model to estimate greenhouse gas emissions from LID facilities and integrated management practices (IMPs) and carbon emissions and sinks of five LID facilities, such as reservoirs. Moore and Hunt [25] analyzed carbon emission pathways in storm-control measures (SCMs) and carbon emission accounting for multiple measures. O'Sulivan et al. [26] studied the environmental effects related to the materials, construction, transport, operation, and maintenance of rain gardens based on an LCA modeling method. Besides, there are many studies on carbon sinks or sequestration as well as CO_2 flux on a single facility, such as a green roof [27], rain garden [28], grassed swale [29], constructed wetland [30–33]. Although these studies have provided precious preference for carbon emissions accounting of storm management measures, they are mostly focusing on one or several certain parts of the whole implementation process. Under this situation, LCA method can be used to consider all implementation phases, which has been used to quantify the environmental impact including greenhouse gas emissions of many technologies and systems [26,34–36] from the whole life cycle. On the other hand, many researches are focused on a single facility or neglect some possible carbon emissions and sinks. Without considering the various carbon emissions and potential carbon sinks comprehensively, as well as various stormwater control facilities and their coupled performance, it is impossible to fully and correctly analyze the carbon emission reduction benefits or the greenhouse effect of Sponge City facilities or LID-BMPs facilities [36].

To address the shortcomings mentioned above, this study chooses LCA method to analyze the carbon emissions and carbon sinks in the whole life cycle of Sponge City projects, takes the characteristics and parameters of actual Sponge City projects into consideration, and develops a comprehensive carbon emission accounting model for Sponge City projects based on the guidelines of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC). A pilot residential community for Sponge City construction in Shanghai is selected as a case study, based on which, the characteristics of carbon emissions and carbon sinks from the whole life cycle can be explored and studied, and several carbon reduction measures can be proposed. This study can contribute to identifying and proposing effective carbon reduction measures, helping planners select facilities with greater carbon sink benefits, and optimizing the overall stormwater management program.

2. Materials and Methods

2.1. Case Study Area and Data

Shanghai is a highly urbanized city, located in eastern China. Due to the high density of impervious roofs and pavements, Shanghai is frequently affected by heavy floods, which have a negative impact on social stability and citizens' life. With the support of the central and local government, Shanghai has been selected as an important pilot city for Sponge City construction. Meanwhile, in recent years, Shanghai has also been constantly striving to strengthen the implementation of carbon emission reduction strategies in various industries. From Zhu's research [37] on the per capita CO_2 emissions of various provinces in China in 2012, as shown in Figure 1, Shanghai's per capita carbon emissions is at the medium level among all provinces. However, considering Shanghai's large population, it is still of great significance for Shanghai to reduce carbon emission. Therefore, it is necessary to account carbon emissions amount of Sponge City projects in Shanghai and find solutions to reduce carbon emission.

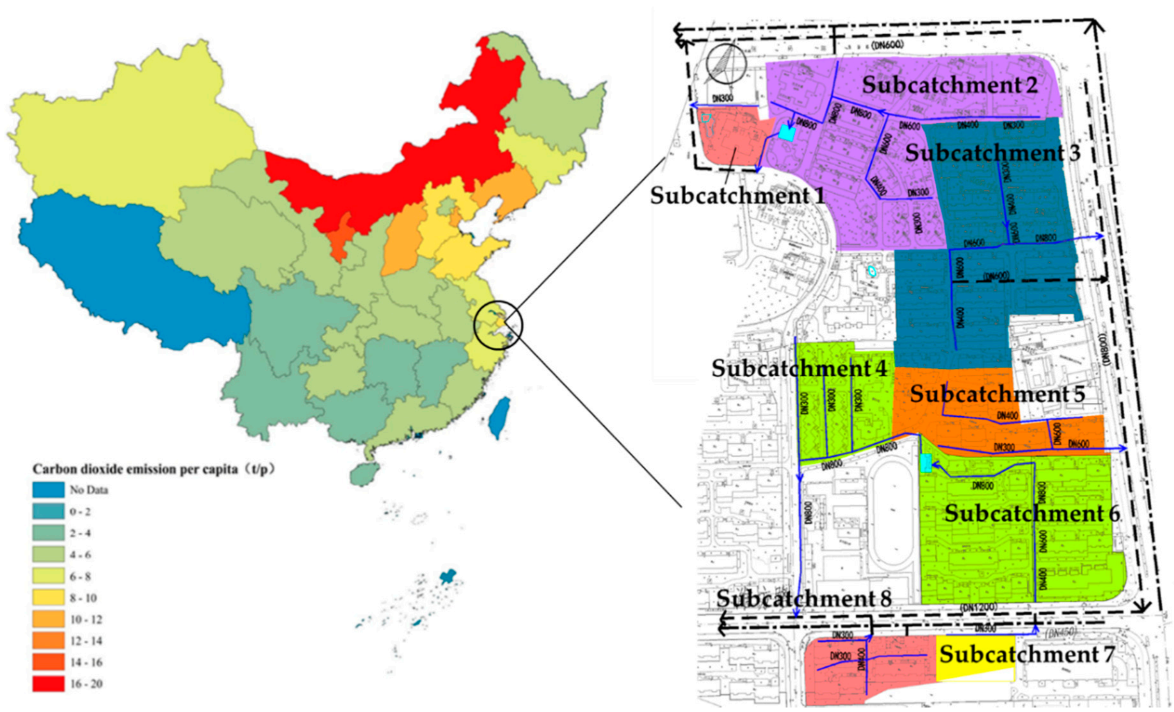

Figure 1. Subcatchment distribution map of the Sponge City project in the residential community.

The accounting model was applied to a pilot residential community in Shanghai, where the Sponge City project is to be implemented, as shown in Figure 1. With a total area of 10.67 hm^2, the Sponge City construction project involves three old and small residential communities. According to the design proposal, a comprehensive rainwater control system consisting of greening modules, ecological buffering modules, and rainwater utilization modules, will be constructed. Within the scope of the project, there are 8 subcatchments in the design plan and technologies such as the grassed swale, rain garden, permeable pavement, and water storage pond are to be applied to reduce at least 75% of total runoff. The inventory of main materials used of facilities construction in this Sponge City project is presented in Table 1, which was obtained from engineering designers and actual construction organizations.

Table 1. Inventories of the Sponge City project in the residential community.

Sponge City Facility	Material Consumption	Value	Unit
Rain garden (2462.2 m^2)	Earthwork	2462.2	m^3
	Planting soil	738.7	m^3
	Permeable geotextile	2954.7	m^2
	Gravel	738.7	m^3
	Impermeable membrane	2955	m^2
	Overflow well	102	
	Polyvinyl chloride (PVC) pipe	847	m
	Plants	2832	m^2
Grassed swale (2800.6 m)	Earthwork	994.9	m^3
	Pebble	31.9	m^3
	Gravel	839.6	m^3
	Planting soil	769.6	m^3
	Overflow well	60	
	PVC pipe	398	m
	Plants	3848	m^2
Permeable pavement (958 m^2)	Permeable brick	745	m^2
	Medium sand	26.82	m^2
	Permeable concrete	89.4	m^3
	Impermeable geotextile	900	m^2
Stormwater storage module (360 m^3)	Intercepting overflow well	2	
	PP module pond	189.65	m^3
	PP module pond	205.7	m^3
	Drain pump	2	
	Electrical cabinet	2	

2.2. Accounting Boundary and Inventory

Determining a reasonable carbon emission accounting boundary is an essential step in studying the carbon emissions of Sponge City facilities. This study uses a LCA method to analyze different phases in the whole process of Sponge City projects, including material production, material transportation, construction, operation, maintenance, and disassembly phases. In the study, the direct carbon emissions, indirect carbon emissions, and carbon sinks of the Sponge City facilities are fully considered. Direct carbon emissions are carbon emissions coming from pollutant degradation. Indirect carbon emissions include carbon emissions from material production, materials transportation carbon emission, and energy consumption by equipment used in different phases. The carbon sink is generated by plant carbon sequestration, rainwater utilization, runoff reduction, rainwater purification, and building energy conservation during the operation of Sponge City facilities. Thus, the carbon emission accounting boundary and inventory can be defined as shown in Figure 2.

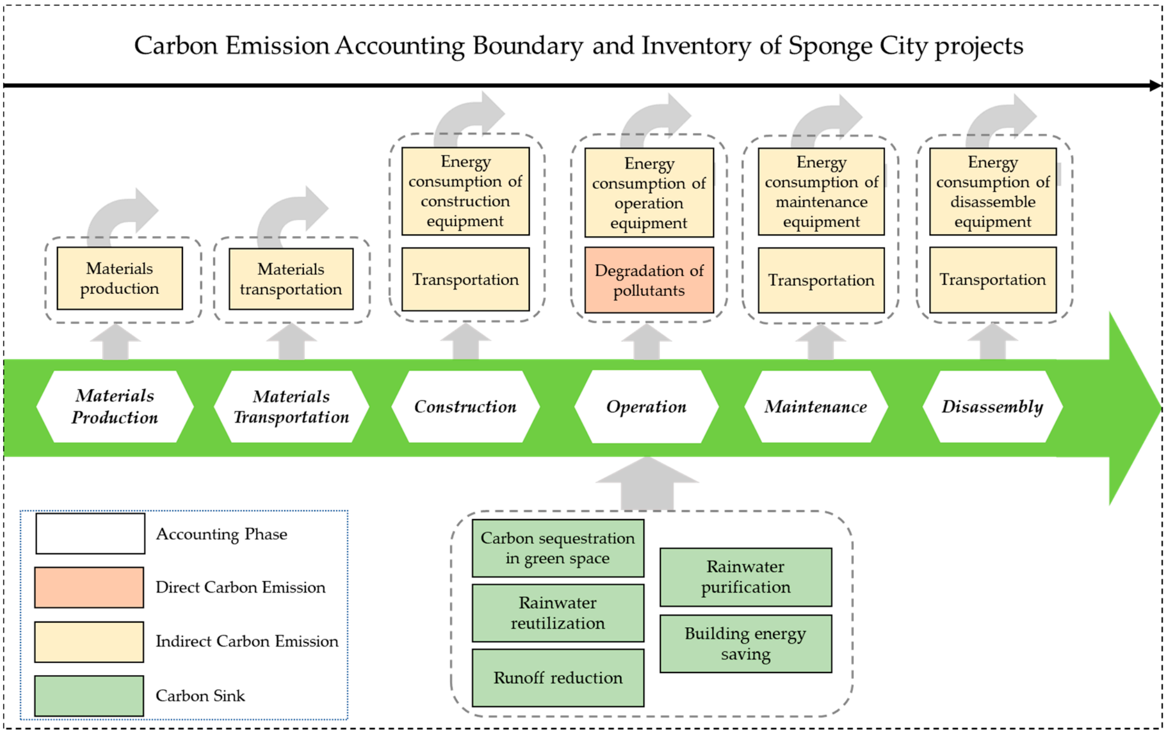

Figure 2. Boundary and inventory of carbon emission accounting for the residential community.

2.3. Accounting Model

This accounting model is based on the methodology of IPCC and adopted the accounting method of emission factors. The amount of net carbon emissions of Sponge City facilities is the total amount of direct carbon emissions plus total indirect carbon emissions and minus the total amount of carbon sinks that can be generated, as shown in the following equation:

$$TCE = (TCE_D + TCE_{ID}) - TCS \tag{1}$$

where TCE is total carbon emissions (net carbon emissions), TCE_D is total direct carbon emissions, TCE_{ID} is total indirect carbon emissions, and TCS is the total carbon sink.

2.3.1. Accounting for Direct Carbon Emissions

The direct carbon emissions of Sponge City facilities come from pollutant degradation during the operation phase, mainly comprised of CO_2, CH_4, and N_2O. Among them, CO_2 and CH_4 are mainly derived from the degradation and conversion processes of organic matter, while N_2O is produced in the denitrification process. According to the IPCC guidelines, since direct emissions of CO_2 are sourced, hence, only the contributions of CH_4 and N_2O are considered in the accounting of direct carbon emissions. Direct carbon emissions can be accounted for using measurement-based or computation-based methods. However, due to the current research on the measurement and calculation of CH_4 and N_2O emissions in the operation of Sponge City facilities, this study calculates the direct carbon emissions in the operation of Sponge City facilities by referring to the accounting methods of CH_4 and N_2O emissions in wastewater treatment.

According to the guidance on the calculation of carbon emissions from wastewater treatment of 2006 IPCC Guidelines for National Greenhouse Gas Inventories [38], the emission factor of methane in the anaerobic decomposition of organic matter is adopted. The CH_4 emission factor can be calculated by the following formula:

$$EF_j = B_0 \times MCF_j \tag{2}$$

where B_0 is the theoretical emission coefficient of methane produced by the anaerobic decomposition of organic matter, the 5 day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD), whose IPCC default factor is 0.6 kg CH_4/kg BOD_5 or 0.25 kg CH_4/kg COD, and MCF_j represents a correction factor for methane emissions in different anaerobic environments, with the value of 0.1 when the wastewater is directly discharged.

Since the degradation of rainwater pollutants in Sponge City facilities are equivalent to the direct discharge of sewage and natural purification, the above formula is suitable to be applied to the direct carbon emission accounting of Sponge City facilities and *MCF* is taken as 0.1. Considering that the global warming potential value of CH_4 is 25 [39], the CO_2 equivalent of CH_4 emissions from Sponge City facilities can be calculated by the following formula:

$$CE_{CH_4} = M_{COD} \times B_0 \times MCF_j \times GWP_{CH_4} = 0.625 M_{COD} \quad (3)$$

where M_{COD} is the amount of COD reduced by Sponge City facilities.

During the accounting of N_2O emissions of Sponge City facilities, the emission factor of N_2O generated by the IPCC for domestic sewage discharge can be considered, with the EF_{N2O} of 0.005 kg N_2O/kg N. Considering that the global warming potential value of N_2O is 298 [39], the carbon dioxide equivalent of N_2O emissions from Sponge City facilities can be calculated by the following formula:

$$CE_{N_2O} = M_N \times EF_{N_2O} \times GWP_{N_2O} = 2.341 M_N \quad (4)$$

where M_N is the amount of nitrogen reduced by Sponge City facilities in rainwater.

2.3.2. Accounting for Indirect Carbon Emissions

The indirect carbon emissions of Sponge City facilities include carbon emissions corresponding to energy consumption, electricity consumption, and material consumption during the whole process of material production, transportation, construction, operation, maintenance, and disassembly. Thus, the total amount of indirect carbon emissions can be calculated as follows:

$$TCE_{ID} = CE_{MP} + CE_{MT} + CE_{ec} + CE_{ET} \quad (5)$$

where TCE_{ID} is the total indirect carbon emissions, CE_{MP} is the carbon emissions from the production of materials, CE_{MT} is the carbon emissions in the transportation process, CE_{ec} is the carbon emissions corresponding to the electricity consumption of the equipment, and CE_{ET} is the carbon emissions corresponding to the energy consumption of the equipment.

(1) *Carbon emissions from materials production*

Carbon emissions from the phase of materials' production primarily comes from the various materials required in Sponge City facilities, which can be calculated by the following equation:

$$CE_{MP} = \sum_i (M_M \times CE_{unit-M})_i \quad (6)$$

where CE_{MP} is the carbon emissions in the production of materials, *i* is the material category, M_M is the consumption amount of the material, and $CE_{unit\text{-}M}$ is the carbon emissions per unit for the corresponding material (carbon emission factors).

Materials utilized in the project mainly include concrete, gravel, polyvinyl chloride (PVC) pipe, permeable membrane, geotextiles, sand, brick, and graded gravel, with their carbon emission factors derived from previous studies [40–44] which have considered the process and energy consumption of local production of these materials in China.

(2) *Carbon emissions from transportation*

The energy consumption and corresponding carbon emissions of transportation depend on the mode of transport, the type of energy, and the distance of transport. Carbon emissions of transportation can be calculated as follows:

$$CE_{MT} = \sum_i (Dist \times M \times CE_{unit-MT})_i \tag{7}$$

where CE_{MT} is the carbon emissions of the transportation process, i is a specific transportation mode, *Dist* is the transportation distance, M is the transportation volume of the material, and $CE_{unit\text{-}MT}$ is the carbon emissions per unit weight of the material and per unit transportation distance, with the value of 0.1759 kg CO_2 eq/(t·km), calculated in combination with data from previous studies [43,45]. Materials to be transported should include all materials and equipment, such as construction materials, construction and operation equipment, and construction waste and earthwork.

(3) *Carbon emissions from equipment*

Relevant equipment is to be used in the construction, operation, maintenance, and disassembly processes. The carbon emissions corresponding to the power consumption of the equipment can be calculated as follows:

$$CE_{ec} = \sum_i (P_i \times T_i \times EF_{ec})_i \tag{8}$$

where i is the type of equipment, CE_{ec} is the carbon consumption of the equipment, P_i is the power of the equipment, T_i is the time of use of the equipment, and EF_{ec} is the emission factor of carbon dioxide from electricity consumption, with the value of 0.8112 tCO_2/MWh in the case which is derived from Baseline Emission Factor of China's Regional Power Grid in 2015 released by the National Development and Reform Commission (NDRC) of China [46].

Some devices are not powered by electricity, but may be powered by energy sources such as coal, diesel, and gasoline. The carbon emissions corresponding to the energy consumption of such equipment are calculated as follows:

$$CE_{ET} = \sum_i (E \times CE_{unit-ET})_i \tag{9}$$

where i is the type of equipment, CE_{ET} is the carbon emissions of the energy consumption of the equipment, E is the energy consumption, and $CE_{unit\text{-}ET}$ is the carbon emissions corresponding to the unit of energy consumption.

2.3.3. Accounting for the Carbon Sink

The carbon sink generated by Sponge City facilities basically comes from the operation phase.

(1) *Carbon sequestration in green space*

In this study, green space is defined in a broad sense, including bioretention measures such as rain gardens, concave green spaces, and ordinary green spaces. Plants and soils in green spaces both have carbon sequestration capacity and their carbon sequestration can be calculated by the following formula:

$$CS_{GA-C} = \sum_i (S_{GA} \times CS_{unit-GA} \times T)_i \tag{10}$$

where i is the Sponge City technical facility category, S_{GA} is the area of the green space, $CS_{unit\text{-}GA}$ represents the unit of carbon sequestration rate of the green space, and T is the accounting period. According to the studies of Wu et al. [47] and other scholars, the carbon sequestration rate depends on the types of plants and several other factors, as discussed in the next section.

(2) *Carbon sink from rainwater utilization*

Through rainwater buckets, rainwater storage tanks, and other facilities, the rainwater can be collected and treated to different degrees and can be recycled, saving a lot of water resources and energy consumption during processing and configuration. The amount of carbon sink from rainwater utilization can be calculated as follows:

$$\begin{aligned} CS_{Reuse} &= \sum_i (Q_r \times CE_{tap-water}) \\ &= \sum_i (Q_r \times QE \times EF_{ec})_i \end{aligned} \tag{11}$$

where CS_{Reuse} is the carbon sink in the process of rainwater utilization, i represents one specific category of Sponge City facility, Q_r is the amount of available rainwater collected by the Sponge City facility, $CE_{tap\text{-}water}$ is the carbon emissions of using equivalent tap water, QE is the amount of the electricity consumed per cubic meter of tap water, and EF_{ec} is the carbon emission factor for the electricity consumption.

(3) *Carbon sink from runoff reduction*

The use of Sponge City facilities can effectively reduce runoff and thus avoid carbon emissions from the drainage network for this part of the runoff, which can be calculated as follows:

$$CS_{Runoff} = \sum_i (M_{runoff} \times CE_{runoff})_i \tag{12}$$

where CS_{Runoff} is the carbon sink generated by the reduction of runoff, i represents one specific category of Sponge City facility, M_{Runoff} represents the amount of reduced runoff brought about by a specific kind of Sponge City facility, and CE_{runoff} represents the carbon emissions that can be saved corresponding to the equivalent amount of runoff discharged by the drainage pipe network.

(4) *Carbon sink from runoff pollutant removal*

Carbon emissions from the treatment of these pollutants in runoff can be avoided while Sponge City facilities reduce runoff. The amount of this kind of carbon sink can be calculated as follows:

$$CS_{Rain-purify} = \sum_i (\sum_j (M_{rain-purify} \times CE_{rain-purify})_j)_i \tag{13}$$

where $CS_{Rain\text{-}purify}$ is the carbon sink generated by runoff pollutant removal, i represents one specific category of Sponge City facility, j represents a category of pollutant reduced by a Sponge City facility, $M_{rain\text{-}purify}$ is the amount of pollutant reduced by a specific kind of Sponge City facilities, and $CE_{rain\text{-}purify}$ is the equivalent carbon emissions corresponding to reduced pollutants.

(5) *Carbon sink from buildings' energy saving*

Buildings' energy saving carbon sinks come mainly from green roofs, which can help reduce the cost and energy consumption of heating or cooling indoor areas of buildings. The carbon sink corresponding to the energy saved for this part can be calculated by the following formula:

$$CS_{Building-energy} = \sum_i (Q_{energy} \times CE_{building-energy})_i \tag{14}$$

where $CS_{Building\text{-}energy}$ is the carbon sink corresponding to the buildings' energy saved brought about by Sponge City facilities, i represents one specific category of Sponge City facility, Q_{energy} is the energy saved by these facilities, and $CE_{building\text{-}energy}$ is the amount of carbon emissions required to provide the corresponding energy. Many researchers have extensively studied the energy saving of a green roof compared with a common roof. Among them, Su [48] found that green roofs can save a significant amount of energy, for example, 19.86 kWh/(m^2·a) compared with a cool roof.

The comprehensive and universal life cycle carbon emission accounting model of Sponge City projects established in this study can be widely applied. However, most of the important carbon emission factors given in the case study were derived from prior research as they were more suitable to be used in the case study due to the location, which aimed at making the accounting more in line with engineering practice, as well as more reasonable and credible. If they need to be used in regions other than the case study site, it is recommended to amend or adopt more appropriate values, since the selection and determination of carbon emission factors have a large impact on the accuracy and rationality of carbon emission accounting [17,49]. In this study, the life cycle of Sponge City facilities is assumed to be 30 years. In addition, due to the linear characteristic of the model, the uncertainty analysis in this study uses a single-factor sensitivity analysis method.

3. Results and Discussion

3.1. Carbon Emissions

According to related research [50,51] on the pollutant removal of Sponge City facilities or LID-BMP practices, 40% of these pollutants can be removed by these facilities. After the setting up of Sponge City facilities in the residential community, the removal capacities for COD and nitrogen pollutants are estimated to be 6307.1 kg COD/year and 492.7 kg N/year, respectively. Based on the above calculation method of the IPCC, the direct equivalent CO_2 emissions of CH_4 and N_2O emissions generated by Sponge City facilities are predicted to reach 3941.9 kg CO_2/year and 1153.5 kg CO_2/year, respectively. The ability of each facility to remove pollutants is a critical factor in determining the amount of direct carbon emissions.

Indirect carbon emissions include carbon emissions from material and energy consumption from the material production, transportation, construction, operation, maintenance, and disassembly phases. According to the foregoing calculation method, combined with the design data of planning and construction of this Sponge City project and the existing literature research, the indirect carbon emissions of each stage of the calculation are shown in Figure 3.

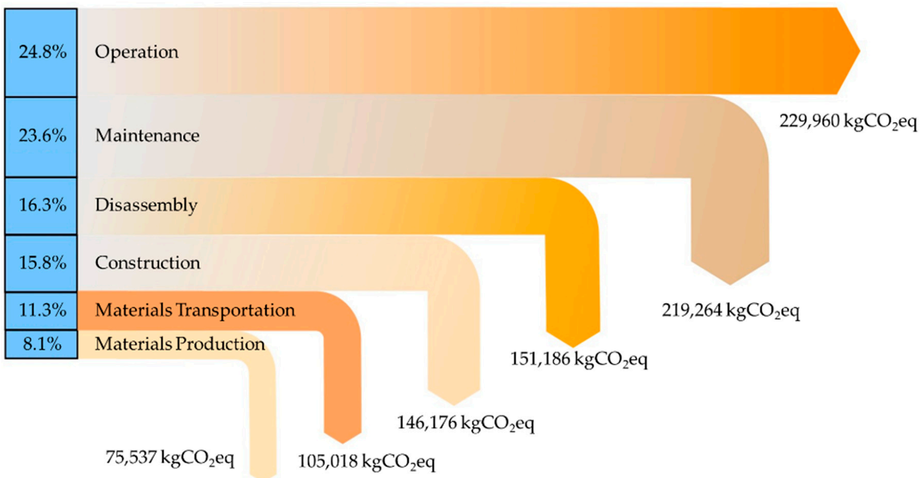

Figure 3. Indirect carbon emissions in the whole process of the Sponge City renovation project.

The proportions of indirect carbon emissions generated during the operation, maintenance, and construction phases are the largest (25%, 24%, and 16%, respectively), and accordingly, the amount of carbon emissions from the disassembly phase is also large. The carbon emissions from these phases can be mainly attributed to the fuel and electricity consumption of the corresponding facilities and equipment and thus are closely related to the amount of energy used and emissions during energy extraction and utilization.

As for the materials transportation phase, the amount of carbon emissions depends on the amount of material being transported, the transportation distances and the fuel consumed. Therefore, the emission reduction measures for this item mainly include the use of clean and renewable fuels, as well as the procurement of building materials in the vicinity to shorten the transportation distance. Although the carbon emissions from the material production phase do not account for a large proportion of the total indirect carbon emissions, they cannot be ignored yet. The carbon emissions of various materials are shown in Figure 4. Among all material used in this Sponge City projects, PVC pipes and impermeable membranes (primarily made of polyethylene (PE)) take significant proportions, in total carbon emission which are, even though the consumption amount of these two materials is not much compared to concrete and other materials. This result is consistent with the research of Xu et al. [52], which showed that the consumption of PVC and fabric contributed significantly to carbon emissions from the LID-BMPs construction phase. The production process of plastics is complicated, thus the amount of carbon emissions from their production phase is relatively huge.

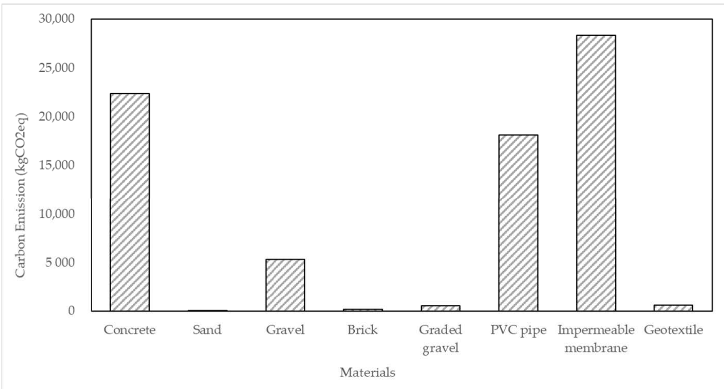

Figure 4. The carbon emissions of various materials from their production phase.

3.2. Carbon Sink

In this Sponge City project, since there are no green roofs and other facilities designed that can generate carbon sinks from the energy saving of buildings and the pipeline network has not been substantially modified, the energy saving carbon sinks and runoff-controlled carbon sinks of the buildings are zero. Three kinds of carbon sinks that can be produced are carbon sequestration in green space, the carbon sink from rainwater utilization, and the carbon sink from runoff pollutant reduction.

Carbon sequestration in green space is a kind of carbon sink achieved by both vegetation and soil in bioretention facilities, such as recessed green spaces and rain gardens. Usually, the exact green carbon sequestration rate can be obtained by direct measurement, but this method is difficult to be carried out, especially for the planning and construction stages. Thus, the emission factor method, based on a large number of literature studies and databases, is an important and convenient way to estimate the amount of carbon sequestration in green space. Wu et al. studied [47] the carbon fixation and oxygen release values of the urban green space in Hangzhou, China, near to the case area in this study, showing that the urban spaces with different kinds of plants have different carbon fixation and oxygen release values. Based on the study of Wu et al., considering that the most frequent plants are evergreen broad-leaved plants, the carbon fixation rate of the rainwater garden and green space in this case study is taken as 2.2255 kg/(m^2·year), with the carbon sequestration rate of plants of 2.184 kg/(m^2·year) and soil of 0.0415 kg/(m^2·year). In this context, the carbon sequestration in the green spaces can be obtained as 5450 kg CO_2 eq/year. The carbon sequestration rate is consistent with the annual net sequestration carbon fixation rate of the constructed wetland in the study of Klein et al. [32], with the range of 0.27~2.4 kg CO_2 eq/year and varying mainly with the season and number of plants. Kim et al. [24] and

Kim et al. [53] found that the reed vegetation in integrated management practices had relatively low net ecological exchange (2.72 kg CO_2/m^2·year) in Korea, compared to that of alternative vegetation such as sedum (3.1 kg CO_2/m^2·year), grass (5.7 kg CO_2/m^2·year), and shrubs (4.9 kg CO_2/m^2·year), which indicated that planting alternative vegetation can effectively reduce greenhouse gases emissions over years by improving CO_2 absorption capacity. Compared with their research, the carbon sequestration rate of the case study is relatively low, maybe caused by the differences in terms of regions and plants. At the same time, this study chooses a relatively lower value within a reasonable range to estimate the carbon emission reduction benefits of Sponge City urban facilities conservatively.

The carbon sink from rainwater utilization also can be achieved in this renovation project. The volume of the rainwater storage tank is designed to be 360 m^3; combining Shanghai rainfall data and related literature research [54], the average annual rainfall frequency in Shanghai can be estimated to be 80 times every year. Under this condition, the amount of rainwater which can be utilized is 17,280 m^3/year. Therefore, combined with the rainfall data from Shanghai, the carbon sink from rainwater utilization which can be achieved by the rainwater storage tank set up in the renovation project contributes the predicted amount of 15,379 kg CO_2 eq/year.

According to Ning et al. [54] and previous research by this group, the event mean concentration of COD in runoff is 144 mg/L and the mean concentration of total nitrogen is about 10 mg/L in Shanghai. Pollutants being removed by Sponge City facilities can reduce the load of wastewater treatment plants greatly and reduce the corresponding carbon emissions. The annual removal amount of COD is 6307.09 kg COD/year and the annual removal amount of nitrogen pollutants is 492.74 kg N/year. Therefore, the annual amount of carbon sink from runoff pollutant removal can be up to 19,552 kg CO_2 eq/year.

3.3. Life Cyle Carbon Reduction

According to the accounting of the carbon emissions and carbon sinks of Sponge City facilities in this residential community, the accumulated carbon sink after 18.8 years can equal the amount of all direct and indirect emissions during the same period (which can be also called as carbon neutralization). In the subsequent lifespan, these Sponge City facilities can function as carbon-emission-reduction system absorbing greenhouse gases from the natural system. The amount of net carbon emission absorbing benefit is estimated to be 25,407 kg CO_2 eq/year, during the last 11 years of the 30-year life cycle.

Therefore, according to the various carbon emissions and carbon sinks, the life cycle flow of the carbon emissions and sinks of the Sponge City project in the case can be presented in Figure 5.

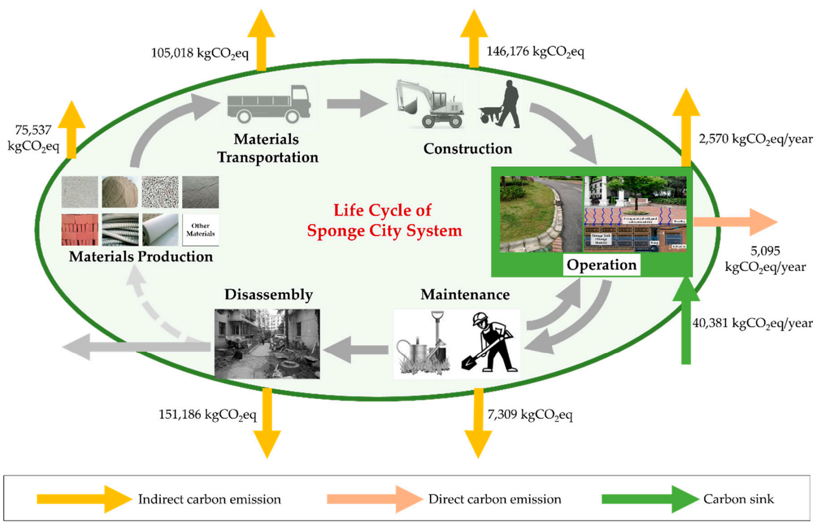

Figure 5. Life cycle flow of carbon emissions and sinks of the Sponge City project.

3.4. Uncertainty Analysis

The results of the single-factor sensitivity analysis can show the effect of some variables on the total life cycle carbon emissions and carbon sinks. The variation range of each factor is set at 10%, and the factors that have a significant impact on the total carbon emissions are operation (2.48%, including direct carbon emissions), maintenance (2.36%), disassembly (1.63%), construction (1.58%), factors related to CH_4 emissions (1.28%), and material utilization (0.81%), which indicated the significance of energy (fuels and electricity) consumption and emission factors. The three most influential materials are concrete (0.24%), PVC (0.20%), and impermeable membranes (0.20%), which proved the above discussion about the materials' production. With a similar method, the impact of three factors on the total life cycle carbon sink benefit are pollutant reduction (4.84%), rainwater utilization (4.98%), and carbon sequestration in green space (1.76%). The uncertainty analysis helps to understand the impact of changes in different factors and can be used as instructions and a reference for identifying carbon reduction measures and policies with high priority.

3.5. Carbon Reduction Measures

Based on the above analysis of carbon emissions and carbon sinks, some measures can be proposed to reduce the carbon emissions and enhance its carbon sink benefits in the Sponge City project's life cycle.

The use of clean and renewable energy and the avoidance of excessive energy consumption is an important way to reduce carbon emissions from many phases mainly including transportation, construction, maintenance, and disassembly phases, which can significantly reduce the total carbon emissions. Many studies have showed that energy saving and efficiency policies were effective in mitigating carbon emissions, and the change in CO_2 emission coefficients for fuels slowed down the increase of residential emissions [17–19]. Substantial waste will be generated during the disassembly phase. If the waste can be recycled and reused rather than being disposed of directly as waste, a considerable amount of carbon emissions can be reduced [21,55]. Many regions, such as Masdar City, Samsø, have been testing renewable energy utilization in recent years, which has proved the advantages and feasibility of carbon emissions reduction [56,57].

Better arrangement of Sponge City projects' implementation can contribute a lot to the reduction of carbon emissions, such as optimization of transport, construction, and comprehensive arrangement. Combined with the uncertainty analysis, the transportation distance has a large impact on the overall carbon emissions and can be shorten to reduce carbon emissions.

More bioretention facilities, such as grasslands and rain gardens, can be set up properly according to local conditions, and meanwhile, the types of vegetation can be reasonably complicated to enhance the performance of the micro-ecosystem, which will help increase the carbon sink benefits of Sponge City facilities. It is not only feasible and significant to deploy these facilities with carbon sink benefit in public spaces, but also to arrange some green facilities on the roofs and walls of buildings, such as green roofs and green walls. In this case study, green roofs are not considered and designed due to the characteristic of the old residential community and economic factors, but solutions and application are necessary to be considered in the near future. Energy savings made by private buildings and deploying facilities with carbon sink benefits in the exterior of the building can help increase the overall carbon sink benefits of Sponge City projects, without having to be limited by the status and availability of public spaces.

Avoiding overuse of plastics and adopting alternative low-carbon materials is also effective on reducing carbon emissions from materials production phase. In contrast, in addition to the large amount of carbon emissions attributable to the vast utilization of concrete, the amount of carbon emissions of sand, gravel, brick, and other building materials is obviously smaller than the amount of carbon emissions of plastics.

A local engineering construction and carbon emission database is also highly recommended to be established and maintained. Although many default carbon emission factors have been given by the IPCC, UNFCCC, ecoinvent, and other organizations or databases, they are not fully applicable to specific cities and specific activities. On the other hand, Sponge City facilities are not the same as conventional stormwater control measures and facilities, and may differ in many aspects such as their structural composition and construction process. Combined with the local conditions of the city, the database with substantial similar activities' data and some carbon emission factors calculated can provide significant value for the selection and determination of factors for the accurate carbon accounting of future projects' planning and implementation.

In addition, if permitted in terms of economy, it is also necessary to install monitoring system and intelligent control system in the community. The monitoring system can help operators to know the operational effects of various facilities better and in a timely way, which is vital for maintenance and taking appropriate control measures. The intelligent control system helps to control the operating parameters of the corresponding equipment in time, optimizing the operation effect and reducing the energy consumption properly. It was estimated that using movement sensors to control lighting and water could cut electricity and water consumption by 51 and 55%, respectively, in Masdar City [56,58], which could contribute a lot to the carbon emissions reduction.

4. Conclusions

In this study, a carbon emission accounting model for Sponge City projects is established, based on the IPCC guidelines and LCA method. A case study in a residential community in Shanghai is presented to analysze the carbon emissions and sinks during the 30-year lifespan of Sponge City facilities. The carbon emissions generated by the operation phase and maintenance phase of the community Sponge City facilities account for the largest proportion, followed by that from the construction, disassembly, and transportation phase. The pollutant removal function of these Sponge City facilities can bring about the largest amount of carbon sink, accounting for 48.4%, followed by the carbon sink generated by rainwater utilization by the rainwater storage tank, accounting for 38.1%. A long-term proper operation can ensure the realization of a large number of carbon sinks. It is expected that carbon neutrality can be achieved in about 19 years and in the latter part of life cycle, the system can function as carbon-emission-reduction system to mitigate the greenhouse effect.

Based on the case study, several measures can be proposed to further reduce the life cycle carbon emissions of Sponge City projects: using low-carbon fuels as energy sources for vehicles and equipment, using low-carbon materials to replace plastics such as PVC and PE with high carbon emissions, purchasing building materials and equipment nearby to reduce unnecessary carbon emission from long transportation distance, and doing better in terms of actual scheme designing and arrangement of implementation. In addition, it is highly recommended to establish carbon emission databases for Sponge City projects to facilitate the carbon emission accounting of various Sponge City projects more accurately, as well as monitoring systems and intelligent control systems.

In future researches, economic feasibility analysis of various Sponge City facilities and related measures or policies on reducing carbon emission can be also incorporated in the carbon emission accounting and reduction.

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