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CARBON REDUCTION ASSESSMENT OF DRAINAGE SYSTEM IN SPONGE CITY- A CASE STUDY IN DONGYING, CHINA

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ABSTRACT

Green infrastructure (GI) is identified as the critical technology to sustainable urban development in the United Nations New Urban Agenda. GI not only has the function of ecological services but also has the function of reducing carbon emissions, which is very important for building low-carbon cities. The carbon emission reduction effect of GI in Sponge City was analyzed by comparing the traditional drainage system (TDS) and the green drainage system (GDS). TDS also indicated combined sewer system (CSS), which undertakes a large amount of urban runoff and transfers it to wastewater treatment plant (WWTP). GDS mainly depends on rain gardens, grass planting ditches, etc., to purify and transfer rain-runoff, so the rain-runoff no longer enters into WWTP. TDS consumes much energy for pumping and wastewater treatment, which produces carbon emissions. GDS reduces the amount of water through the pumping station and sewage treatment plants resulting in a significant reduction in carbon emissions. In order to assess the carbon reduction effect of GDS, a new set of calculation has been proposed. Taking Dongying (Shandong province, China) as an example, the carbon-reduction benefit of the drainage system in Sponge City is calculated based on hydrological datasets and the carbon emission coefficients. The results show that the carbon emission is reduced by 54.3%, 43.3%, and 38.9%, for wet, normal and drought year, respectively.

Keywords: Low carbon city, Green Infrastructure, Carbon Reduction Effect, Sponge City, Drainage System

1. INTRODUCTION

Global warming has become a severe problem that could not be ignored [1,2]. Nowadays, more and more cities in the world aim at developing low-carbon models [3-5]. China also plays an essential role in mitigating climate change [6,7]. China has promised to reduce carbon emissions per unit of GDP by 60%~65% by 2030 compared with 2005. By the end of 2018, the urbanization rate of China had reached 59.98%, which indicated that China's urbanization construction is still in a rapid development stage. The stormwater drainage system is a crucial and necessary infrastructure in urban construction. However, there are several problems in the construction mode of the traditional stormwater drainage system in the process of urbanization in China. The core issue is the gray engineering infrastructure, including drainage networks, pumping stations, etc. This gray engineering has been heavily invested but has not fundamentally solved the urban water problems such as flood disaster, water resources shortage, water environment deterioration. Large amounts of greenhouse gases are generated during the construction and management of gray engineering infrastructure, which contribute to global warming and also bring significant challenges to urban construction and urbanization development. Moreover, as a result of global warming, the extreme weather including heavy rain and drought has aggravated the urban water problem, leading to a vicious circle in the process [8].

In order to alleviate the severe urban water issue, China is implementing a "Sponge City" plan nationwide [9]. In the Sponge City of China, green stormwater infrastructure is adopted to achieve a virtuous urban hydrological circle, including stormwater infiltration, interception, storage, purification, reuse, discharge, etc. to promote the natural accumulation, natural infiltration, natural purification. At present, there are several similar concepts to Sponge City worldwide, such

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as Low Impact Development (LID), Best Management Practices (BMPs), Sustainable Urban Drainage System (SUDS), Water Sensitive Urban Design (WSUD) and so on [10]. These infrastructures follow a low-carbon pattern of stormwater management, since they have lower cost and energy than traditional gray infrastructure in material production, transport, construction, and operation, and are a low-carbon pattern of stormwater management [11,12]. Green infrastructure (GI), an essential part in the urban water system, is of considerable significance to the realization of the low-carbon city. Carbon emission accounting and carbon reduction effect assessment are necessary. Scholars have tried to study the carbon emission accounting system for GI [13-17], in which the life cycle assessment method has been widely used.

In summary, the existing researches have focused on the life-cycle carbon emissions of the green stormwater infrastructure and the differences in carbon emissions between green stormwater infrastructure and traditional infrastructure. While at the larger urban scales, the carbon emission reduction benefits of GI in urban hydrological cycle are in blank. In fact, the main difference between green stormwater infrastructure and gray infrastructure is the change of urban hydrological cycle. The utilization of GI would reduce the pressure on the drainage system, and therefore the requirement of drainage capacity and pollution reduction capacity of drainage system will decrease. Meanwhile, the carbon emission will reduce in the drainage system. This research introduces a method to quantify the carbon reduction benefits of Sponge City drainage system in the hydrological cycle for urban areas, so that one can fully understand and evaluate the benefits of energy-saving and environmental protection in Sponge City construction.

2. THE PRINCIPLE OF CARBON EMISSION REDUCTION OF SPONGE CITY IN THE PROCESS OF HYDROLOGICAL CYCLE

2.1 Carbon Emission Pattern in Hydrological Cycle of TDSs

Traditional stormwater drainage systems can be divided into two types according to whether they are combined with sewage systems or not. The first type is combined sewer system (CSS) (as shown in Fig 1-A), which refers to the drainage way for collecting and transporting stormwater and sewage from the same pipe system. At present, CSS in China is generally the interception type. The interception type of CSS refers to the confluence of domestic sewage, industrial wastewater, and stormwater in street pipes and canals, discharging to the intercepting trunk pipe. The domestic sewage and industrial wastewater in CSS are all transported to wastewater treatment plant (WWTP) on the days without rainfall. When it rains, if the total quantity of stormwater, domestic sewage, and industrial wastewater exceeds the fixed interception ratio, the excess amount of water is discharged into the downstream channel through overflow wells. Since it is generally gravity flow in the combined piping network (CPN), the carbon emission pattern in this hydrological cycle process includes the carbon emission from the forced drainage of stormwater in pumping station (PS) and the carbon emission from the energy consumed by the treatment of stormwater entering WWTP. The second type is the separated drainage system (SDS) (as shown in Fig 1-B).The stormwater runoff flows through the stormwater piping network(SPN) and PS during rainfall, and is discharged into the downstream river without any treatment. In order to solve the issue of combined system overflow (CSO), many cities in China are also putting the transformation from CSS to SDS into practice. However, the problem of black-and-malodorous water body cannot be solved only by SDS. The reason is that the non-point source pollution caused by initial stormwater is even severer than that caused by point source pollution sometimes. In this process, the carbon emission pattern is mainly the carbon emission from the energy consumed by the forced drainage of stormwater from pumping stations.

2.2 Benefits of Carbon Emission Reduction of Sponge City System in Hydrological Cycle

The Sponge City construction under way in China adopts green drainage system (GDS) to resolve the drawbacks of the TDS. The small-scale, dispersed and low-cost green infrastructure (GI) is adopted to replace partial gray infrastructure. The stormwater management is carried out by simulating the natural hydrological cycle process [18,19]. Therefore, the urban water problem is effectively alleviated, the investment in construction is saved, and the cost of energy consumption and carbon emissions are reduced. Consequently, the low-carbon drainage system is effective. GI includes rain gardens (RG), green roofs (GR), pervious pavement (PP), stormwater tanks (ST), grass planting ditches (GPD), grass swales (GS), stormwater ponds (SP), stormwater wetlands(SW) and so on. Stormwater is stored and purified in source, process and end to reduce runoff, and is drained directly through the surface, resulting in the reduction of the amount of stormwater entering SPN, PSs and WWTPs (as shown in Fig 1-C).

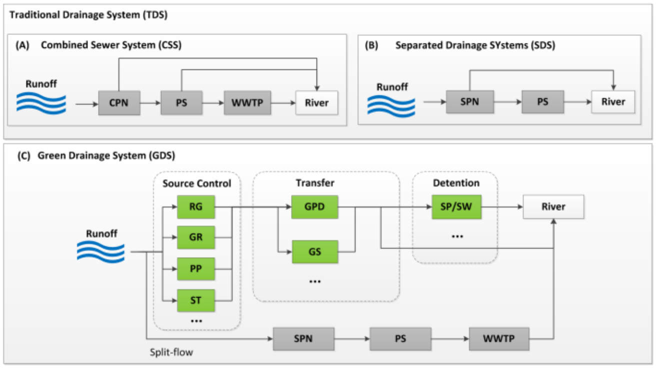

Fig 1 Hydrological process of traditional drainage system (TDS) and green drainage system (GDS)

In the process of hydrological cycle, the benefits of carbon emission reduction of Sponge City system mainly include three aspects:

Reducing Energy Consumption of Pumping Station (PS)

GI can effectively reduce the total amount and peak flow of runoff and alleviate urban waterlogging through retention, infiltration, storage and reuse of stormwater. Meanwhile, GI can discharge stormwater runoff nearer to rivers through surface drainage channels such as grass planting ditches, thus the amount of stormwater forced discharged by PSs and the carbon emissions of PSs are reduced.

Reducing Energy Consumption of Wastewater Treatment Plant (WWTP)

Sponge cities effectively store and purify stormwater by the source dispersion. Meanwhile, the stormwater is discharged into rivers or lakes nearby. through overground drainage channels such as grass planting ditches. A small amount of seriously polluted stormwater is cut off and discharged into the sewage pipe network, then effectively reducing the amount of stormwater entering WWTP by the combined sewer system (CSS). Therefore, the energy consumption and carbon emissions of WWTPs can be reduced.

Reducing Energy Consumption of Water Supply System (WSS)

The utilization rate of stormwater resources is increased by stormwater collection, and the amount of water supply for landscape and ecological environment are reduced through storage of stormwater by GI. Thus, the carbon emissions from the water supply system are reduced.

Through the analyses above, it can be concluded that the GDS has changed the carbon footprint of TDS pattern in the process of hydrological cycle, and the carbon emission reduction is remarkable.

3. MATERIALS AND MRTHODS

3.1 Study area

Dongying City is located in the northeastern part of Shandong Province in China, which is the delta of the Yellow River estuary. The study area, with a total area of 323.8km^2, is the central area of Dongying City. The mean annual precipitation of the study area is 550-600 mm, mostly concentrated in the summer. The precipitation from July and August accounts for approximately half of the annual precipitation, which tends to cause drought and flood disasters. The drainage system of the central city is still a rain and sewage combined system. There are 10 existing WWTPs and 36 existing stormwater PSs in the study area, and the actual treated sewage volume is about 385,000 m^3/d. In 2016, a Special Plan for Sponge City in the central area of Dongying City was initialized. According to the plan, the central area of Dongying City is divided into 18 drainage sub-areas. Through the construction of the GI in each control unit, the total annual runoff control rate of 75% can be achieved. After the Sponge City is completed, most of the stormwater will be discharged through GI into the river from the surface by the form of gravity flow. Meanwhile, the sewage will enter the WWTP through sewage piping network. The data which is used for the construction of drainage system is mainly from the planning documents and announcements of the Dongying Municipal Government.

3.2 Methods

3.2.1 The carbon emissions from hydrological cycle process in traditional drainage pattern

The operation power consumption of stormwater pumping station for discharge of stormwater can be calculated by Equation (1)[20]:

$$E_S = \frac{\rho g h Q}{3.6 \times 10^6 \times \eta} \tag{1}$$

Where ES is the energy use of pumping station (KWh); ρ is the density of water (kg/m^3); g is the acceleration of gravity (m/s^2); h is the average head of pumping station (m), which is set to 5; Q is the amount of stormwater discharge through pumping station; η is the engine efficiency, which is generally taken as 0.75.

Q can be calculated by Equation (2) [21]:

$$Q = P_a F \varphi - V \quad (2)$$

Where Pa is mean annual precipitation; F is the service area of the pumping station; ϕ is the comprehensive runoff coefficient, which is set to 0.6; V is the amount of annual stormwater re-utilization, which is set to 0.

When the stormwater pumping station is running, the carbon emissions are mainly from the power consumption. The carbon emissions can be calculated by Equation (3):

$$C_E = E_S \times EF \quad (3)$$

Where CE represents the carbon emissions from the power consumption; ES is the energy use of pumping station; EF is the emission factor for the power consumption, which is set to 0.766kgCO_2/KWh [22].

The energy consumption of WWTP in dealing with stormwater runoff during rainfall is divided into two parts. The first part is generated by the degradation of COD to generate CH_4 and CO_2. This part can be calculated by the method proposed by the Intergovernmental Panel on Climate Change (IPCC) guidelinesThe flux of CH_4 and CO_2, produced in dealing with a roll of water by a sewage treatment plant, can be calculated by the method. The emission factor of CH_4 is 0.00186kg CH_4/kg COD, and the emission factor of CO_2 is 0.161 kg CO_2/kg COD [23]. The second part is carbon emissions caused by electricity consumption. The average power consumption of urban sewage treatment plants in Dongying is 0.29KWh/m^3. The COD content of stormwater runoff in study area is 280 mg/L, and 40% of the runoff treated by WWTPs per year.

3.2.2 Accounting for carbon emission reduction benefits in Sponge City

After the construction of the Sponge City in Dongying City, the initial stormwater is cut off and discharged into the pumping station and sewage treatment plant. The remaining rainfall is absorbed and discharged through the green infrastructure, effectively reducing the amount of water entering the sewage treatment plant and pumping station. The Split-flow is 3mm. At present, the water supply for greening and ecological environment in Dongying City is tap water. After the construction of the Sponge City, the stormwater can be stored and recovered through stormwater collection facilities, which can effectively reduce the corresponding water supply. The return rate of stormwater is 10%. The carbon emission reduction benefits of Sponge City can be calculated by reducing carbon emissions handling the same quantity of water through the corresponding traditional facilities. The power consumption of the treatment and supply of 1m^3 tap water is taken as 0.65kWh [20].

3.2.3 Rainfall Data

Based on the rainfall data of the hydrologic station in Dongying City, the precipitation frequency work is carried out, and then the Pearson III curve is applied. The precipitation that meets the hydrologic station's precipitation frequency at 25%, 50%, and 75%, are recorded as three levels: wet, normal and drought. And through calculation, it is found that the wet, normal and drought years are 1987, 2011 and 1981, and annual rainfall is 656.6mm, 518.2mm and 435.2mm, respectively. Annual carbon emissions and carbon emission reduction benefits are calculated under conditions of different level years.

4. RESULT

4.1 Carbon emissions in TDS

For the three levels, Wet year (H1), Normal year (H2), and Drought year (H3) under TDS pattern, the carbon emissions caused by PS are 1773.3t, 1399.5t and 1175.4t per year, respectively. The carbon emissions generated by WWTP are 13661.7t, 10782.0t and 9055.1t, respectively (as shown in Fig 2).

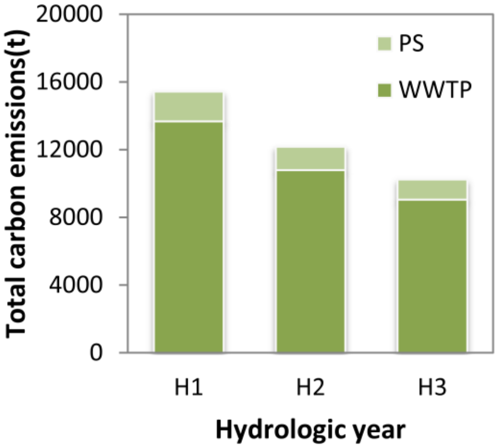

Fig 2 Carbon emissions in TDS in three different hydrological years during hydrological cycle

4.2 Carbon emissions in GDS

For the three levels, Wet year (H1), Normal year (H2), and Drought year (H3) under GDS pattern, the carbon emissions caused by PS are 348.4t, 340.8t and 308.7t per year, respectively. The carbon emissions generated by WWTP are 6710.2t, 6564.5t and 5945.5t, respectively. The results are summarized in Fig 3 below.

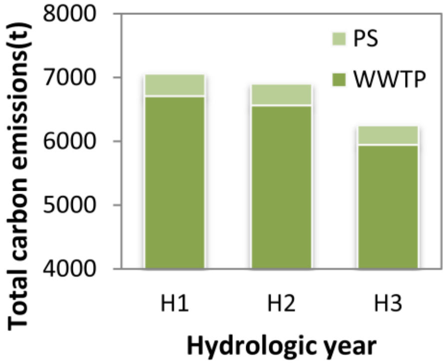

Fig 3 Carbon emissions in GDS in three different hydrological years during hydrological cycle

4.3 Carbon reduction effects in GDS

In the process of hydrological cycle, GDS could directly reduce the carbon emissions of PS and WWTP in TDS, and indirectly reduce the carbon emissions of Water Supply System (WSS) through the recycling of stormwater. In Wet year (H1), Normal year (H2) and Drought year (H3), total carbon emissions in both PS and WWTP are reduced by 54.3%, 43.3%, and 38.9%, respectively. The total carbon reductions in WSS are 6351.4t, 5012.7t and 4209.8t, respectively. The results are summarized in Fig 4, as shown below.

5. DISCUSSION

Rainfall events in Dongying are mostly in summer, which is an uneven distribution throughout a year. Sponge city helps cities better adapt to climate. The monthly carbon reduction benefits of Sponge City drainage system can be further analyzed combining hydrological data in the study area.

GDS has some additional carbon reduction effects, such as relieving heat island effect [24], reducing the energy consumption of air conditioner [25], carbon sequestration by vegetation[26], etc., which are not be quantified in this research.

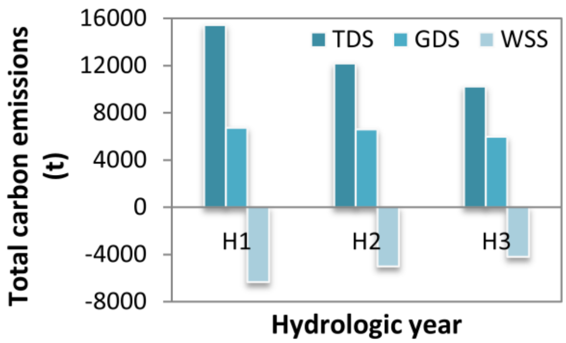

Fig 4 Carbon reduction effects in GDS in three different hydrological years during hydrological cycle (The negative number indicates the reduced carbon emission of WSS after adopting GDS)

6. CONCLUSION

In order to comprehensively quantify and evaluate the energy-carbon reduction effects of sponge city drainage system, a method to quantify the carbon reduction benefits of Sponge City drainage system in the hydrological cycle for urban areas was established. In the study area, after implementation of GDS, the carbon emission reduces by 54.3%, 43.3% and 38.9%, for wet, normal and drought year, respectively.

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