Cost-effectiveness Analysis in Low Impact Development of Qinxin District, Qingyuan City, Guangdong China

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Abstract. In recent years, thanks to extreme weather like storms and downpours, flood events have occurred frequently worldwide, endangering the personal and property safety of citizens. Most developed regions use low impact development (LID) measures to prevent flooding and other water-caused disasters. However, the laying cost of LID is expensive, and the utility of LID is different based on different types of LID facilities. Given the flood news in the Qingxin District of Qingyuan City, which caused plenty of citizen lives and property losses, it is necessary and urgent to study the drainage system plan and construction in this place in order to prevent another blow from bad weather in the future. Therefore, this paper aims to study the cost-effectiveness of various types of LID by the precipitation data of Qingyuan so as to find out how to reduce flood inundation at the lowest cost. The results demonstrate that the covered area of vegetative swale is simply 600m^2, and it can reduce most runoff and outflow. Besides, multiple LIDs can reduce nearly 40% of runoff and overflow in the most significant gap. Based on the reliable simulation analysis and former research, it can be concluded that the vegetative swale is the most cost-effective facility toward other LIDs, and the permeable pavement is the worst efficiency measure.

Keywords: Low impact development; Cost-effectiveness; Drainage system; Floods.

1. Introduction

According to the Ministry of Emergency Management of the People's Republic of China, there were 38 regional heavy rainfall in China in 2022, with a total precipitation of 606.1 mm, down five percentage points compared with the same period in many years. In 28 provinces, 626 river channels had flood peaks exceeding the warning value, 10 flood peaks appeared in the main river, and two gigantic flood peaks successively appeared in the Pearl River region. In South China, there are 9 regional heavy precipitation events, among which the Pearl River region is the historical record from 1961 to 1961, and there have been regional heavy precipitation events. During the years, 33.883 million people were affected by floods, of which 171 people were killed, killed or unaccounted for, and economic losses amounted to $128.9 billion. In addition, there were 5,659 landslide collapses and mudslides caused by flooding in the country. The number of deaths from flooding in the United States peaked in 2015 when 176 people were killed by flooding. In recent years, the number of deaths from flash floods and river floods in the United States has generally increased. As for economic damages, floods and flash floods caused an average of more than $3 billion in property and crop damage across the United States. North American countries had the highest economic losses due to floods and flash floods in 2017, at about $60.7 billion. Therefore, the measures of urban rainwater management are urgent, and this report aims to discuss the cost-effectiveness of sustainable urban drainage systems and explain how Low Impact Development (LID) can fix the terrible situation.

The drainage system is vital for a city to manage the urban rainwater. The number of extreme storms reported worldwide has increased since 1992, so urban drainage systems need to become more efficient. LID is an effective urban drainage scheme, such as rain gardens, bioretention facilities, vegetated rooftops, permeable pavements, and rain barrels. It combines drainage and water storage, most commonly used in North America. There is a water storage system around each drainage node and drainage pipe, which minimizes the pressure on the sewer pipe and stores water for the irrigation system for regular use. By implementing LID principles and practices, water management can reduce the impact on the built area and promote the natural movement of water in the ecosystem or watershed.

Simultaneously, LID can maintain or restore river basins' hydrological and ecological functions in many applications. The LID system has an artificial wetland system to filter the surface rainwater runoff and return it to the sewage system. Therefore, the system can timely treat the stagnant water that cannot be discharged in time by underground water pipes.

As for evaluation methods, the earliest benefit assessment was mainly based on a comparative study with traditional stormwater control facilities [1], which showed that the construction cost of LID was lower than that of grey infrastructure, and the effect of urban stormwater management was far better than that of traditional stormwater management mode. With the gradual increase of discussions on the cost-effectiveness of LID, a large number of studies have begun to appear, trying to explore the design and optimization of LID to achieve a balance between environmental benefits and cost input. Currently, the methods of cost-effectiveness evaluation include the life cycle method, construction cost method, cost-effectiveness analysis method and the combination of hydrological model and algorithm [2].

In recent years, Qingyuan City has been affected by rain disasters, involving many buildings collapsing, flooding and so on. Therefore, this study uses the Qingxin district of Qingyuan city district as the research area and uses the construction cost method and cost-effectiveness analysis to compare various LID facilities. This study designs a small community as the test object and discusses how LID can avoid disasters similar to this Qingxin district, as well as the cost-effectiveness of setting LID facilities in this area for social and economic aspects. Meanwhile, the study analyzes LID structure, urban improvement and cost after installation and shows the characteristics of the LID system based on the installation of the LID system in a region.

2. Principle of LID

LID benefits water resources does not take rivers as places to absorb pollution, and does not damage the grass gullies and slopes along the water bank. Through infiltration, storage, regulation, retention and other means, control at the source, prevent non-point source pollution and protect the water and water ecosystem's self-purification system. Meanwhile, the hydrological characteristics can remain unchanged before and after LID development. LID benefits topsoil by collecting it during land development, restoring it after that, protecting and making good use of topsoil resources, and preventing soil erosion. The topsoil layer is the top layer of soil that contains more organic matter and humus and has higher fertility. Topsoil plants have developed roots, which is the basis of vegetation growth, and the microbial content is the most abundant. Topsoil can permeate, store and purify precipitation during rainfall, which is the key to surface water infiltration. LID changes soil infiltration and water storage capacity by changing soil texture, bulk density, aggregate, organic matter and other physical and chemical properties while reducing surface runoff. The purpose of infiltration, storage and purification can be achieved by adding permeable pavement, permeation pond, permeation well, permeation pipe and permeation channel to the topsoil and vegetation.

LID is friendly to terrain, and the catchment pattern formed by natural terrain is essential to regional development. Urban development must respect the original terrain of the land and try to maintain the landform, climate and water cycle of the land. LID should study the different catchment patterns and influences of the original and post-development terrain. According to the topography, continuous natural waterfront should be constructed, natural defence lines with high vegetation cover should be established in areas prone to erosion, the natural texture should be dredged, urban water system should be connected, water surface area should be increased, urban meltwater capacity should be improved, and groundwater supply should be increased, such as ecological ditches, stranded wetlands, rivers and lakes. In addition, LID is also friendly to vegetation. Vegetation is a product that conforms to the terrain and is also a product of water and soil. In turn, vegetation could protect the terrain, water and soil. LID can effectively penetrate and recharge groundwater through the blessing of vegetation. In LID development, vegetation plays an important role, such as promoting natural infiltration, reducing surface runoff, increasing rainwater evaporation, alleviating the urban heat island effect, reducing flood speed and water volume of rainwater entering rivers, reducing pollutants, and controlling non-point source pollution. Nevertheless, different LID facilities have different prices and effects that should be selected and extensively used based on the cost-effectiveness of different types of them.

3. Background

Qingxin District, located in Qingyuan City, Guangdong Province, is an inland urban area subject to flooding due to extreme weather (Fig. 1). According to a post issued by the Publicity Department of Qingxin District Committee of the Communist Party of China in June 2020, in June 1994, eight areas of Qingyuan City were affected by severe tropical storm No. 3. This grievous natural disaster is characterized by the rapid, concentrated and long duration of heavy rain, which caused the water level of the Beijiang River to rise sharply. At 22:00 on June 19, the water level of the Beijiang River reached 16.34 meters, 4.34 meters above the warning level, 0.46 meters above the 1982 Qingyuan flood disaster event, and the highest recorded record in Qingyuan. The continuous heavy rain in Qingxin district, coupled with the continuous rise of the Beijiang water level, caused the flood disaster seriously. In just three days, 24 towns and villages in Qingxin were affected, more than 2,300 natural villages and the affected population reached 485,000 people, accounting for 79.5% of the country's population, 23 kilometres of 9 embankments were overtopped, 4,132 houses were destroyed, 16,100 hectares of crops were soaked, and floods surrounded 7,200 people in one day. It can be seen that the sustainable drainage measures in the Qingxin district of Qingyuan city are of great necessity for improvement.

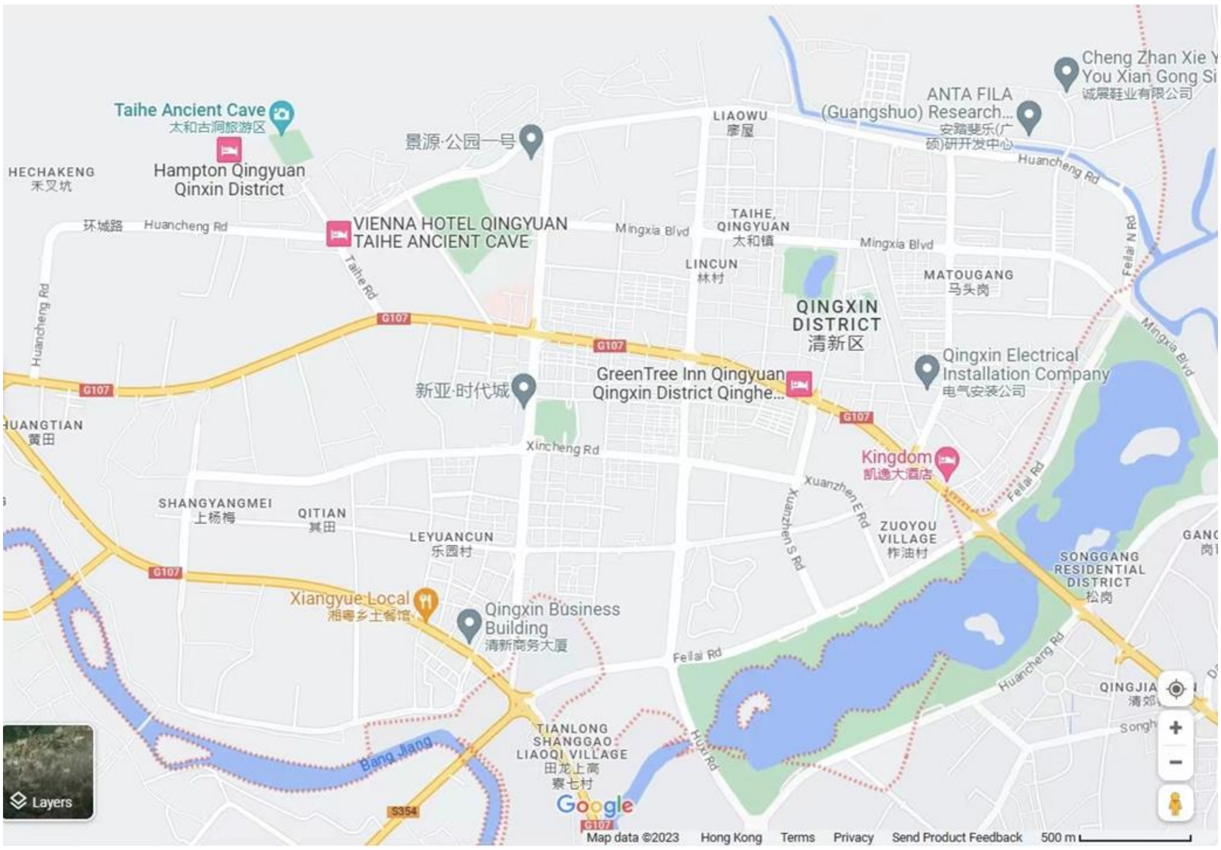

Fig. 1. The location of Qingxin district of Qingyuan city, Guangdong, China.

4. Methods

Based on the China Meteorological Administration data, the sustained rainfall from Qingyuan rainfall data on August 8, 2021, is shown in Table 1, indicating a continuous downpour on that day.

According to the hydrological information released by the Hydrology Bureau of Guangdong Province in June 2022, the water supply sources of Qingxin district in Qingyuan city are Daqin and Longxudai reservoir, and the local reservoir data are obtained according to the National Water and Rain Information Site, as shown in Table 2.

Table 1. Qingyuan rainfall data on August 8, 2021.

Time(hr)	00	01	02	03	04	05	06	07	08
Precipitation(mm)	27.6	28.8	29.9	32.5	33	34.3	34.4	32.8	32.0
09	10	11	12	13	14	15	16	17	18
29.7	29.7	29.3	28.7	28.2	28.1	28.1	28.1	28.0	28.1
19	20	21	22	23	24				
27.9	26.3	26.2	26.1	26.2	26.5				

Table 2. Reservoir data from real-time water situation of large reservoirs.

River Basin	Region	River	Reservoir	Water level (m)	Storage capacity $(million\ m^3)$	Flow (m^3/s)
Zhujiang	Guangdong	Qinhuang River	Daqin	64.1	5	2
Zhujiang	Guangdong	Huangdong River	Longxudai	257.98	41	17

Figure 2 shows the pipe network of the Qingxin district. The small community model is built up as Figure 3 in stormwater management model (SWMM), and four kinds of LID blocky models (including 7 vegetative swales, 17 rain barrels, 14 permeable pavements and 9 rain gardens) are set up. The system model with LID and the system model without LID have the same precipitation set-up based on Table 1, shown in Figure 4. As for the LID model setting, the surface berm height of permeable pavements and the thickness of the soil and pavement is set as 1.5m, and that of storage is 2m. The berm height and thickness of the green roof are set as 2m, and the flow coefficient of the rain barrel is 16. The vegetation volume fraction for vegetative swales is 0.9, and surface roughness is 1500.

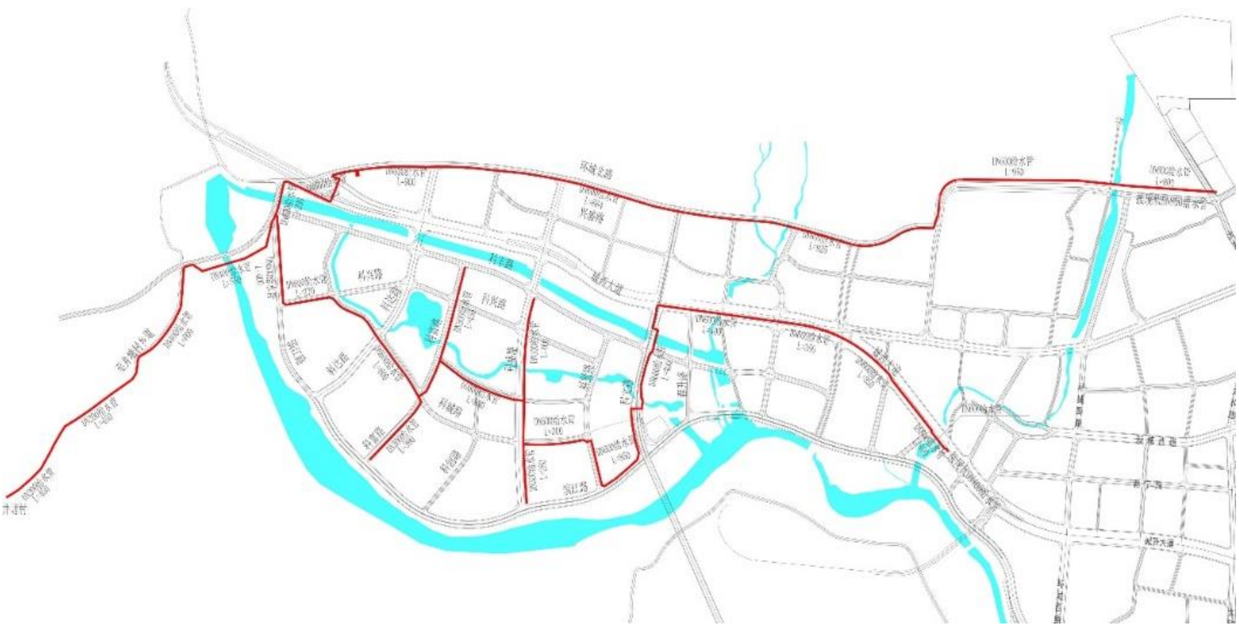

Fig. 2. Pipe network of the Qingxin district.

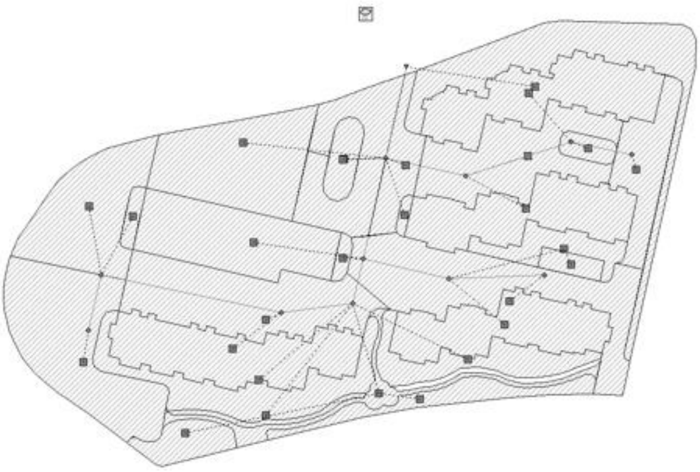

Fig. 3. The SWMM model of a small community in the Qingxin district.

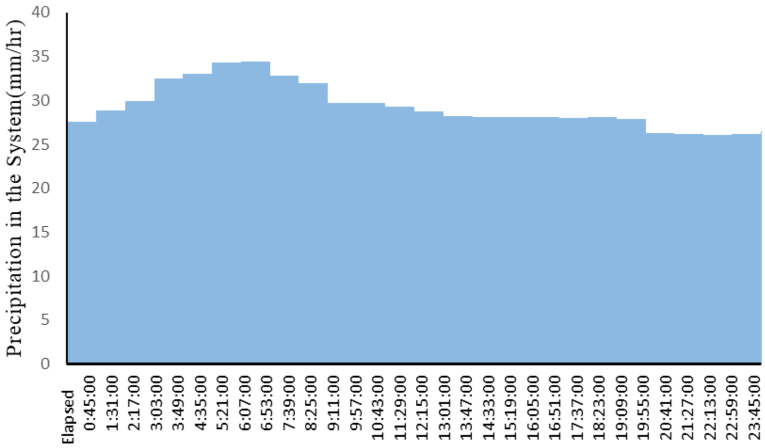

Fig. 4. Precipitation in the System.

5. Results

Urban runoff is an essential source of microplastic pollution [3]. Reducing the runoff can decrease urban solid pollution to keep the drainage system clear and unobstructed. According to the output data, it can be seen from Figure 5 that the runoff in the system without LID is always higher than that with LID, and when the gap is the largest, the runoff with LID is 37.5 percentage points lower than that without LID. Reflecting LID Settings can significantly help reduce surface runoff and effectively prevent flooding and other water disasters.

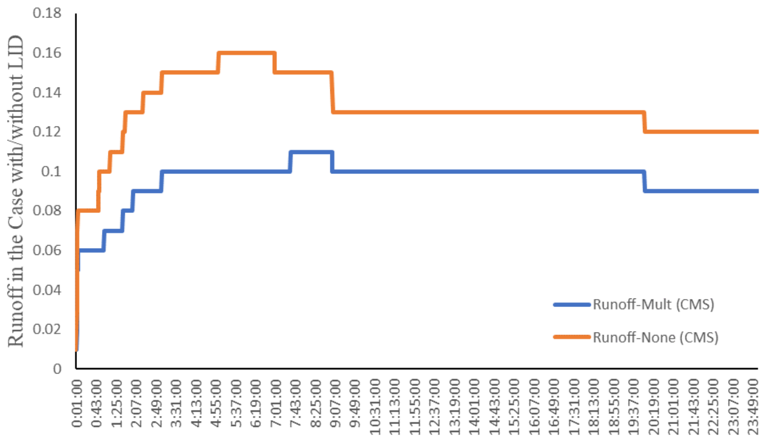

Fig. 5 Comparison of runoff in the case with/without LID

The system outflow in the cases has the same feature. Figure 6 shows that the outflow in the system without LID is always higher than that with LID, and when the gap is the largest, the outflow with LID is 38.5 percentage points lower than that without LID. It reflects that part of rainwater is collected by rain barrels or absorbed by vegetation or soil of LID to prevent flooding and achieve sustainability.

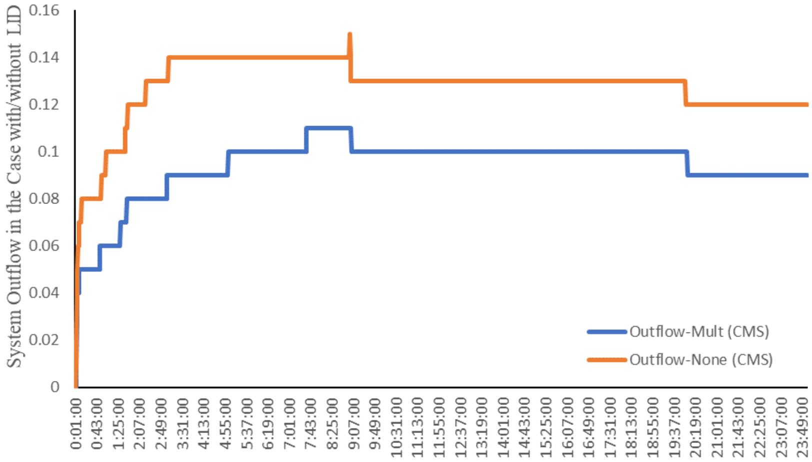

Fig. 6. Comparison of system outflow in the case with/without LID.

Based on Figure 7 and Figure 8, the capability of these 4 kinds of LID is similar, and both can greatly reduce runoff and outflow and store water simultaneously. According to the graph, runoff attenuation through infiltration in vegetated swales is the majority, accounting for most load reductions [4].

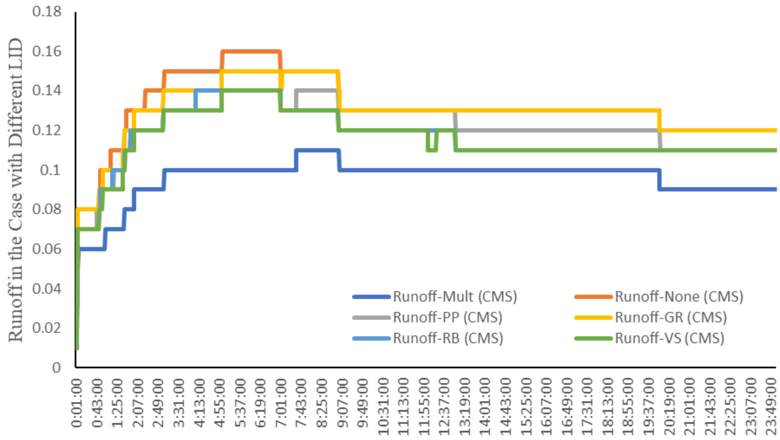

Fig. 7. Comparison of runoff in the case with different LID.

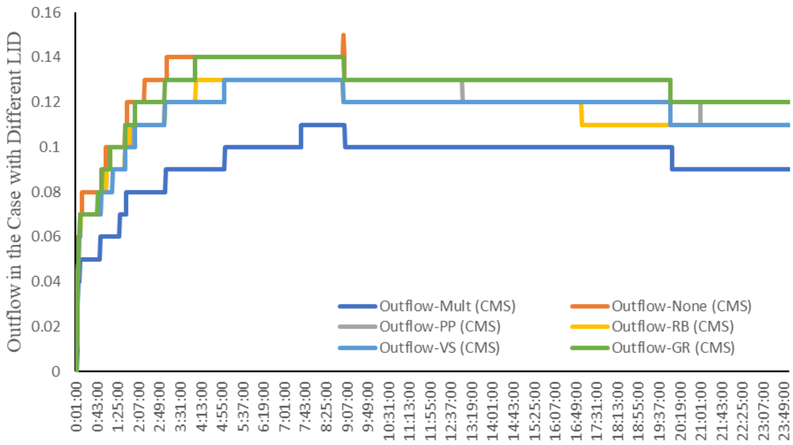

Fig. 8. Comparison of outflow in the case with different LID.

6. Analysis and Discussion

The information provided by the Ministry of Housing and Urban-Rural Development shows the price of different kinds of LID in Table 3.

Table 3. The cost of different kind of LID.

LID	Price (CNY/m^2)
Permeable Pavement	60-200
Green Roof	100-300
Bio-Retention Cell	150-800
Sunken Green Space	40-50
Pond Wetland	400-600
Rain Barrel	800-1200
Rain Garden	500-700
Vegetative Swale	30-200

The community has 7 vegetative swales, 17 rain barrels, 14 permeable pavements and 9 rain gardens. Therefore, the area can be calculated as below:

$$N_{PP} = 2 + 15 + 30 + 300 \times 2 + 200 \times 2 + 150 + 50 + 100 \times 5 = 1747m^2 \tag{1}$$

$$N_{RB} = 200 \times 4 + 100 \times 3 + 2 + 10 + 160 + 80 + 20 + 60 + 50 \times 2 + 30 + 40 = 1602m^2 \tag{2}$$

$$N_{GR} = 200 + 20 \times 2 + 5 + 50 \times 4 + 100 = 545m^2 \tag{3}$$

$$N_{VS} = 100 + 40 \times 2 + 200 + 80 + 50 + 150 = 600m^2 \tag{4}$$

The cost of the LID in that area can be calculated as below:

$$P_{PP} = [1747 \times 60, 1747 \times 200] = [104820, 349400]\ CNY \tag{5}$$

$$P_{RB} = [1602 \times 800, 1602 \times 1200] = [1281600, 1922400]\ CNY \tag{6}$$

$$P_{GR} = [545 \times 100, 1747 \times 300] = [54500, 163500]\ CNY \tag{7}$$

$$P_{VS} = [600 \times 30, 600 \times 200] = [18000, 120000]\ CNY \tag{8}$$

Considering the similar efficiency, it can be concluded that vegetative swale is the most cost-effective, and rain barrel is the least cost-effective, with a price difference of 22 times. Nevertheless, the rain barrel is valuable and can store rainwater in the dry season in case of unexpected needs. So, a rain barrel is necessary but can be set less to balance the construction costs. In summary, based on the indispensability of rain barrels, permeable pavements have the lowest economic conversion rate and are fungible. Therefore, permeable pavements can be constructed and utilized less in practical projects.

According to the technical guide for Sponge City construction issued by the Ministry of Housing and Urban-Rural Development in 2014 [5], the maintenance frequency of each LID is shown in the table below. The maintenance price of LID facilities per square meter can be calculated according to the data in the "Simulation Study on the Cost and Benefit of Rain Flood Management of Sponge Facilities Based on the Whole Life Cycle" [6]. The above data are shown in Table 4.

Table 4. The maintenance cost of different kind of LID.

LID	Maintenance frequency(per year)	Maintenance cost(per m^2)
Permeable Pavement	2	1133
Green Roof	2-3	756
Bio-Retention Cell	2	/
Sunken Green Space	2(and mow the grass per month)	/
Pond Wetland	2(and mow the plaint per year)	/
Rain Barrel	2	/
Rain Garden	3	756
Vegetative Swale	2(and mow the grass per month)	567

As seen from the above table, the maintenance times of the four LID measures are similar, among which permeable pavement is the most expensive, vegetative swale is the cheapest, and the price difference per cubic meter is nearly twice as much. Therefore, regarding the efficiency and sustainability of measures, permeable pavement is always unworthy in terms of cost-effectiveness, and vegetative swale is the most cost-effective and sustainable.

Some research presents that vegetative swales can also reduce chemical oxygen demand (COD), total suspended solids (TSS), turbidity, nitrate, phosphorus, iron, and zinc [7]. Removal of those by the planted vegetation is very high [8]. It can be seen that the extensive construction and adoption of vegetative swales could certainly bring high water treatment benefits to the Qinxin district.

It is crystal clear that Qingxin, a district of the urban city Qingyuan, can use more vegetative swale and reduce the use of permeable pavement to decrease the cost of construction and maintenance. The cost-effectiveness and construction priority of the four LID facilities is 1. Vegetative swale, 2. Rain barrel, 3. Green roof, and 4. Permeable pavement. By the analytical data above, LID can make Qingxin's drainage system workable and sustainable and increase its capacity for deranging and handling at the lowest cost to effectively prevent flooding and avoid personal and financial losses. On the other hand, it is suggested to combine two or more systems to treat drainage, and multiple sustainable urban drainage systems can reduce a lot of runoff and outflow. For instance, the rain barrel-urban garden, which is a combination of the use of rain barrels and green gardens, reduces operation during the growing season and requires that the rain barrel function to benefit the garden and to reduce roof runoff and system runoff [9, 10]. It is pronounced that multiple combined sustainable urban drainage systems in Qinxin can effectually mitigate urban flood irrigation.

7. Conclusion

This study simulates the drainage system by comparison of installed LID facilities in Qingxin District, Qingyuan City, Guangdong Province. Based on the construction and maintenance costs and output benefits of LID, the cost-effectiveness of various types of LID is calculated, and suggestions are given on the efficiency of various LID construction schemes. For cost-effectiveness, vegetative swale is the best, followed by rain barrel, green roof, and permeable pavement. It is suggested that multiple systems be combined to deal with drainage, and a large amount of runoff and outflow can be reduced under the joint action of multiple low-impact development facilities. In summary, the diversified LID combined system of Qinxin City can effectively alleviate urban flood disasters. In diversification, the proportion of vegetative swale should be increased as much as possible. In contrast, the proportion of permeable pavement should be reduced to increase the efficiency and ability of LID facilities to reduce the accumulation of rainwater in fresh areas to a greater extent because of its relatively small covered area and affordability for the government.

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